A SOIL WATER BALANCE MODEL
FOR GRAIN SORGHUM UNDER
WIDE SPACED FURROW
IRRIGATION

By

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LIST OF SYMBOLS

β	stage 2 drying coefficient, cm/$t^{1/2}$
Eo	potential evaporation above the crop canopy, cm/day
Ep	evaporation from the plant or transpiration, cm/day
Es	evaporation from the soil surface, cm/day
Es_1	Stage 1 evaporation rate, cm/day
Es_2	Stage 2 evaporation rate, cm/day
Es'	evaporation from WSFI Region 1, cm/day
Es''	evaporation from WSFI Region 2, cm/day
Es'''	evaporation from WSFI Region 3, cm/day
Eso	potential evaporation below the crop canopy, cm/day
ϵ	albedo
ϵs	albedo of a bare soil
ϵc	albedo of a grain sorghum canopy at full cover
H	net radiation, Ly/day
I	irrigation application, cm
l	distance between furrows, cm
l_i	distance assigned to WSFI evaporative region i, cm
P	precipitation, cm
Q	soil water lost to runoff or deep perculation, cm
Sw	extractable soil water in the root zone, cm
t	time, days
U	upper limit of Stage 1 drying, cm

UL maximum level of extractable soil water held in the profile, cm

ULw Maximum level of extractable soil water held in the profile during a WSFI event, cm

ΣE_{s1} cumulative evaporation from the soil during Stage 1 drying, cm

ΣE_{s2} cumulative evaporation from the soil during Stage 2 drying, cm

CHAPTER I

INTRODUCTION

The Oklahoma Panhandle and the entire High Plains region is characterized by low rainfall coupled with high evaporative demand. These facts make the addition of supplemental irrigation water a necessary requirement in the cultivation of many crops. Depletion of the Ogallala aquifer and increased economic pressure have necessitated the study of alternative irrigation practices, to maintain the economic feasibility of irrigated agriculture in the region. Wide spaced furrow irrigation (WSFI) has shown promise as a possible means of maintaining or increasing crop yields while reducing the quantity of irrigation water applied. However, the mechanism behind the WSFI response is not clearly understood. Stone et al. (1979) suggested the benefit of WSFI arose from reduced evaporation from the soil surface, since the entire surface of the field was not wetted during a WSFI event. However, the measurement of soil evaporation in the field is costly and time consuming. A well known grain sorghum growth model, SORGF, was considered as a possible means of investigating the properties of the soil water balance under WSFI conditions. However, the original version of SORGF did not allow for the application of irrigation water in a nonhomogeneous fashion, such as with WSFI. Thus, the main objective of this study was to develop a new algorithm for use within the existing model which would accurately describe changes in the soil water balance throughout the growing season under WSFI. The growth of grain sorghum could then be simulated under every furrow irrigation (EFI) and WSFI conditions and compared to actual field data.

CHAPTER II

REVIEW OF LITERATURE

Wide Spaced Furrow Irrigation

The most common mode of furrow irrigation is the application of water to every furrow in the field. This method of 'every furrow irrigation' (EFI) is characterized by a relatively short distance between each furrow, perhaps 1 m , with 1 or 2 planted rows between adjacent furrows. The result is a relatively homogeneous application of water in which the entire surface of the field is thoroughly wetted on the day of an irrigation event.

Other forms of furrow irrigation have been devised in an attempt to increase irrigation efficiency and conserve water. These include: skip row irrigation, alternate furrow irrigation, alternating-alternate furrow irrigation, and wide spaced furrow irrigation (WSFI). Some confusion has developed concerning the definitions of the above techniques. WSFI is defined as the application of water to furrows spaced a least 2.5 m (8 ft.) apart, and is limited to fine-textured soils where lateral and downward movement of water are approximately equivalent (Stone et al., 1979, 1985). Alternate furrow irrigation is the application of water to every other furrow and was studied for example by

Newman (1968), and Musick and Dusek (1974). However, their irrigated furrows were less then 2.5 m apart and were not WSFI by definition. Alternating-alternate furrow irrigation (A-A) also involves the application of water to every other furrow. However, on the subsequent irrigation, water is applied to the furrows which remained dry during the previous irrigation. Thus, each furrow in the field receives water on every other irrigation day. The above techniques can result in a nonhomogeneous application of water in which portions of the field surface remain dry during an irrigation event.

Stone et al. (1979) summarized studies involving several of the above methods that were applied to a variety of crops, including grain sorghum. Results suggested that WSFI had the potential of increasing irrigation efficiency and conserving water while maintaining reasonable yields. Studies conducted at Goodwell, OK, by Stone et al. (1982), compared EFI to a combination of alternate and alternating-alternate WSFI in grain sorghum. Results indicted that WSFI could produce water savings of 20 to 50 percent, depending upon management and climatic factors. Continued experimentation at Goodwell, OK, by Stone et al. (1985) and Tsegaye (1986) indicated that when a given amount of irrigation water is applied, a combination of A-A and WSFI methods will produce higher yields in grain sorghum than EFI methods. Stone et al. (1979) have suggested that the benefit of WSFI is the result of reduced evaporation from the soil surface since the entire surface of the field is not saturated during an irrigation event. Since the premise of this thesis involves alternating-alternate WSFI, it will simply be referred to as 'WSFI' from this point forward.

Evaporation from the Soil

Water losses from the plant and soil surface, collectively defined as evapotranspiration, ET, are important components in the soil water balance. Since evaporative losses from the soil alone can account for up to 50 percent of the ET term (Griffin et al., 1966), a great deal of research has been preformed to learn more about the process. Several papers include a review of this literature, including Hide (1954), Lemon (1956), and more recently Idso et al. (1974). Laboratory experiments have shown that evaporation from an initially wet soil occurs in three defined stages (Fisher, 1923; Penman, 1941; Hide, 1954; Lemon, 1956; Philip, 1957). The first stage (Stage 1) is characterized by a constant rapid loss of water which is controlled by the amount of energy reaching the soil surface, or the environmental demand. During this stage, soil pores near the surface are saturated, and water is supplied to the surface from below via capillary flow. As time progresses the soil surface begins to dry and forms a layer of resistance to upward water movement. At this critical point (Penman, 1941) there is a marked reduction in evaporation caused by the change from liquid to vapor flow. This event marks the beginning of the falling rate stage (Stage 2) and is limited by the water content distribution and hydraulic properties of the soil (Gardner and Hillel, 1962). It should be emphasized that the transition from Stage 1 to Stage 2 evaporation is very abrupt. Russel (1950) reported that evaporation rates were rapidly reduced to 10 percent of their previous value after evaporation exceeded the critical point. The third stage of evaporation is characterized by a very low evaporation rate in which water movement is controlled by adsorbtive forces between the liquid and solid phase. Since this stage has little effect on the soil water balance, more effort has been expended on the study of the first two stages of evaporation. Idso et al. (1974) were apparently the first to observe the three stages of evaporation under field conditions.

The above principles have led to the development of several models for the prediction of evaporation from the soil, Es. Ritchie (1972) introduced a model which made independent estimates of Es and the evaporation from the plant, Ep, based on potential evaporation calculations using a the Penman equation (Penman, 1963). He found excellent agreement between modeled and observed soil water values in grain sorghum, except when the leaf area index was high and the soil surface was wet. Ritchie believed this error was due to an overestimate of Ep, which was based on an empirical relationship between the leaf area and potential evaporation, Eso. Tanner and Jury (1976) used a similar method to calculate Es, but estimated the value of Eso using the Et formula of Priestley and Taylor. Comparisons of simulated and observed soil water levels in potatoes indicated improved performance. Other models for the prediction of Es have been introduced which consider water flow and distribution within the soil profile. Hillel (1975) simulated the diurnal fluctuations in Es, while van Bavel et al. (1976) considered the concurrent effect of water and heat flow.

CHAPTER III

DESCRIPTION OF THE MODEL

History

The grain sorghum growth model, SORGF, was developed as a cooperative project between the Texas Agricultural Experiment Station and the ARS-USDA division, at the Blackland Agricultural Research Station, Temple, Texas. The model was developed during the early and mid 1970's, and received input from a team of researchers from different scientific disciplines. Arkin et al. (1976) presented the first official reference to the model as a complete unit. Model inputs and components were mentioned and generalized to highlight the philosophy and applicability of the model. Specific components used within the model have received attention on their own accord. Ritchie (1972) developed the soil water balance model currently used within SORGF, while Arkin et al. (1978), and Vanderlip and Arkin (1977), reviewed light interception and yield components, respectively. Although the model was made available to other scientists in 1976, the first user's guide to the model was released later by Maas and Arkin (1978). This document presented the main components within the model, along with the corresponding FORTRAN WATFIV source code. A set of test data and model input parameters were included, together with the corresponding simulation output. This allows a new user to test his version of the model for accuracy and integrity.

Inputs and Structure

The SORGF model requires various input data and model parameters which correspond to a predetermined field situation. The input parameters required for a complete simulation are a combination of plant parameters, field geometry and location data, and daily climatic data (Table 1). The model also has the unique ability to update certain plant parameters throughout the growing season as that data becomes available. This feedback characteristic is indicated in the name of the model, SORGF. Feedback parameters which can be used during a growing season are presented in Table 2.

The structure of the model hinges around a continuous loop which increments calendar day, stepping one day each cycle. On each day the model uses the climatic data for that day to flow through a combination of ten major modules, which simulate the growth of a single average plant. A simplified flow diagram is given in Fig. 1. Each module is presented with its corresponding assigned name for future reference. The major function of each module is as follows:

TABLE 1.

Required model input parameters and data.[1]

Plant Parameters	
	Number of Leaves
	Maximum leaf area for each leaf, cm^2
Field Geometry and Location Data	
	Date of planting, calendar day
	Planting depth, cm
	Plant population, plants/ha
	Row spacing, cm
Daily Climatic Data	
	Maximum Temperature, °C
	Minimum Temperature, °C
	Solar Radiation, Ly/day
	Rainfall, cm

[1] (Arkin et al., 1976)

TABLE 2.

Possible SORGF daily feedback parameters.

Date of emergence
Date of leaf emergence for each leaf
Leaf area for each leaf on day of feedback
Date each leaf achieves maximum area
Weight of each plant organ on day of feedback
Stage of development on day of feedback

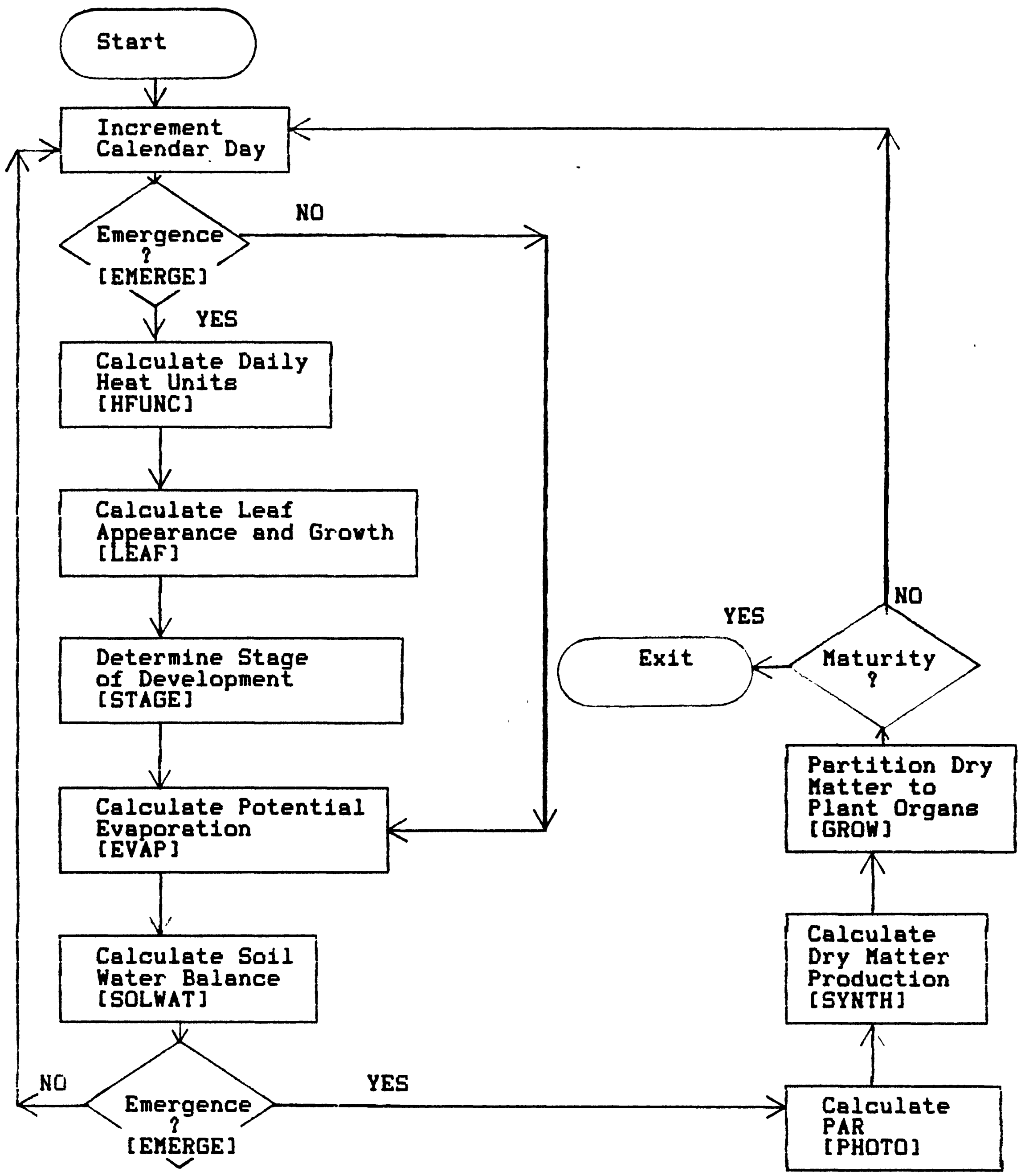

Fig. 1. Simplified flow diagram of SORGF.

EMERGE: Determines the date of emergence as a function of accumulated heat units since the date of planting.

HFUNC : Calculates the heat units above some preassigned base temperature.

LEAF : Determines the calendar date on which each leaf appears and the leaf area of that leaf on a daily basis.

STAGE : Determines the stage of development for the growing sorghum plant.

EVAP : Calculates the potential evaporation above and below the canopy as a function of climate data.

SOLWAT: Calculates the soil water balance based on inputs, in the form of rainfall and irrigation, and outputs based on estimates of the evaporation rate from the plant and soil surface.

PHOTO : Calculates the intercepted photosynthetically active radiation, PAR.

SYNTH : Calculates the production of dry matter as a function of potential photosynthesis.

GROW : Partitions dry matter into various plant organs, including the root, leaves, culm, head, and grain.

Although this description may seem relatively simple, one must realize that each module is composed of various submodels and mathematical formulas. It should also be noted that the model is deterministic in nature, containing no randomly generated variables. Thus, simulations using the same input parameters and climate data will produce the same result.

The Soil Water Balance

The soil water content over the growing season has a large impact on the rate of plant development and final yield. Thus, any model which intends to simulate plant growth, must be able to accurately estimate the soil water content in the profile throughout the growing season. The accounting of soil water gains and losses can be described with a soil water balance equation similar to that used by Stegman (1983)

$$I + P = (Ep + Es) + Q + dS \qquad [1]$$

where;

I = Total irrigation applied
P = Precipitation
Ep = Evaporation from the plant
Es = Evaporation from the soil
Q = Deep percolation and runoff
dS = Change in total soil water content

Evaporation from the plant and soil are collectively called evapotranspiration, ET, and are the major forms of water loss in the field. While Ep is used by the plant for physiological purposes to generate growth, Es is lost to the environment with little or no benefit to the crop. The magnitudes of I and P are a function of management and climate, respectively, while the value of Q can be held to a minimum by proper irrigation management.

The SORGF model calculates changes in the soil water balance based on simple "checkbook" computations using given or estimated values of the variables in equation

[1]. At any given time, the soil profile contains a certain quantity of extractable water, Sw, that is available for plant use. The value of Sw can never exceed the predetermined maximum value of extractable soil water, UL, which is dependent on the water holding characteristics of the soil in question. Soil water additions and losses are simply added or subtracted, respectively, to calculate the new value of Sw on a daily basis by equation [2].

$$Sw_{(t)} = Sw_{(t-1)} + I + P - (Es + Ep + Q) \qquad [2]$$

All the water represented by Sw is assumed equally available to the plant and no considerations are taken for the distribution of roots or water in the soil profile. The depths of irrigation and rainfall are simply read from the simulation's corresponding data file, while $Sw_{(t-1)}$ is obtained from the previous day's result. When an excessive quantity of water is added to the system, such that the value of Sw would exceed UL, the value of Q is calculated instantaneously by equation [3].

$$Q = (Sw_{(t-1)} + I + P) - UL \qquad [3]$$

It should be noted that no sophisticated estimates of drainage or runoff are made within the model.

The SORGF model uses daily climatic data as well as soil and plant characteristics to make estimates of soil and plant evaporation. Each simulation day the model first calculates the potential evaporation above the plant canopy, Eo, as a function of net radiation. This term can then be used to make an estimate of the potential evaporation below the plant canopy, Eso, based on the magnitude of leaf area index, LAI. It should be noted that the original soil water balance model developed by Ritchie (1972) used a Penman expression to calculate Eo and Eso. However, the current version of SORGF appears to use a Preistley-Taylor equation as described by Tanner and Jury (1976). These calculations are performed within the EVAP module (Fig. 1), and require temperature, solar radiation, and leaf area data on a daily basis.

Estimates of plant evaporation are made using a relationship similar to the one developed by Ritchie and Burnett (1971) using empirical data from studies of grain sorghum and cotton in central Texas. They found, when water movement to the plants was not limiting, evaporation from the plant could be estimated by equation [4].

$$Ep = Eo(-0.21 + 0.8LAI^{1/2}) \qquad [4]$$

$$0.1 \leq LAI \leq 2.8$$

However, the SORGF model uses a similar relationship given in equation [5].

$$Ep = 0.53(LAI)^{1/2}Eo \qquad [5]$$

$$0.0 \leq LAI \leq 3.0$$

The differences between equations [4] and [5] are very minor for a given evaporative demand and LAI value, and since the value of Ep must equal zero before emergence

(LAI=0), equation [5] was probably created for computing ease. If the magnitude of LAI exceeds 3.0 then Ep = Eo.

The SORGF model estimates soil evaporation by applying the model introduced by Ritchie (1972). Evaporation rates during Stage 1 drying are considered equal to the potential evaporation below the canopy, Eso. Ritchie defined the critical point, U, between Stage 1 and Stage 2 drying in terms of the cumulative Stage 1 evaporation, ΣEs_1. Thus, evaporation rates proceed at Eso until $\Sigma Es_1 > U$. On that day, denoted as the transition day, Es = Eso until $\Sigma Es_1 = U$, then for the remaining portion of the day Es = 0.6Eso.

Black et al. (1969) have shown by solution of the flow equation that the cumulative evaporation during Stage 2 drying can be described using equation [6]

$$\Sigma Es_2 = \beta t^{1/2} \qquad [6]$$

where β is a constant which must be determined for a given soil, and t represents days after Stage 2 drying begins. The initial value of ΣEs_2 can be determined on the transition day, which allows the rearranging of equation [6] to solve for t in equation [7]

$$t = (\Sigma Es_2/\beta)^2 \qquad [7]$$

where t represents the starting time for Stage 2 evaporation. On the next day, t is increased by one day and Stage 2 evaporation can be calculated by equation [8].

$$E_{s2} = \beta t^{1/2} - \beta(t-1)^{1/2} \quad [8]$$

It is important to note that the values of U and β are dependent on soil properties, and must be adjusted for the location in question. Estimates of evaporation along with the corresponding soil water balance calculations are made within the SOLWAT module of SORGF (Fig. 1).

Applicability to Research

The characteristics of the SORGF model make it an excellent research tool for the study of growth and production of grain sorghum. The fact that most major modules have an effect on the resulting output from other modules, allows for testing interrelationships among growth characteristics and management practices. Since calculations are made on a daily basis, the results of each simulation day include the combined effect of all previous simulation days. This allows for the study of management events which occur on a daily basis, such as the irrigation of the field. The one major disadvantage of the model is that many relationships were developed using empirical data collected near Temple, Texas. Thus, the model may require calibration when simulations are attempted for regions or situations vastly different than those used during model development.

CHAPTER IV

MATERIALS AND METHODS

Origin of Observed Data

The calibration and execution of the SORGF model for a specific location and situation required several inputs. Since one of the main objectives was to compare simulated results to observed data, the model was calibrated with parameters developed for that location. Experiments conducted by others over the 1984 and 1985 growing seasons at the Panhandle Research Station at Goodwell, OK, provided an excellent database of soil water content over depth and time, and of crop yield (Tsegaye, 1986). A randomized complete block design with three replications and four treatments was used to study the effect of both WSFI and EFI methods. The treatments were composed of two irrigation frequency levels and two modes of water application. Table 3 shows the four treatments used along with the seasonal quantity of irrigation water applied during both years. Treatments 1 and 2 were designed to receive the same quantity of water within a given year. That is, the WSFI plots received water twice as often as the EFI treatment, but received only half as much water as the EFI

TABLE 3.

Field treatments used over the 1984 and 1985 growing seasons at Goodwell, OK.[1]

Treatment	Irrigation Frequency (days)	Total Irrigation Water Applied -1984- (cm)	-1985-
1. EFI	14	37.0	37.0
2. WSFI	7	37.0	33.0
3. EFI	21	30.0	22.0
4. WSFI	10.5	26.0	21.0

[1] (Tsegaye, 1986).

plots on the day of an irrigation. The same philosophy was applied to treatments 3 and 4 which received a smaller quantity of irrigation water. The reason some of the treatments did not receive equal amounts of water as planned, was due to the omitting of the last irrigation of the season since the crop had reached maturity. Grain sorghum (Sorghum bicolor L. Moench. cv. Pioneer 8501) was planted on 1.4 m wide beds. Two rows were planted per bed, separated by a distance of 0.66 m. Thus on the day of an EFI event irrigated furrows occurred every 1.42 m, while during a WSFI event irrigated furrows were 2.84 m apart. Soil moisture data was collected approximately every 3 days using the neutron scattering method, and measurements were made to a depth of 120 cm during 1984 and 180 cm during 1985. In both years soil water content measurements were made at 15 cm depth increments, starting at 15 cm below the surface. Two access tubes for each treatment plot were located in the planted rows. Fig. 2 describes the field geometry and the position of the access tubes at the Goodwell site. The soil type at this location was a Richfield Clay Loam, classified as a fine montmorillonitic, mesic, Aridic Argiustoll.

Daily climatic data was obtained by others from observations taken in conjunction with a separate experiment located at the same station (Sternitzke, 1986). A Campbell Scientific CR21 Micrologger[1] and associated

[1] Campbell Scientific

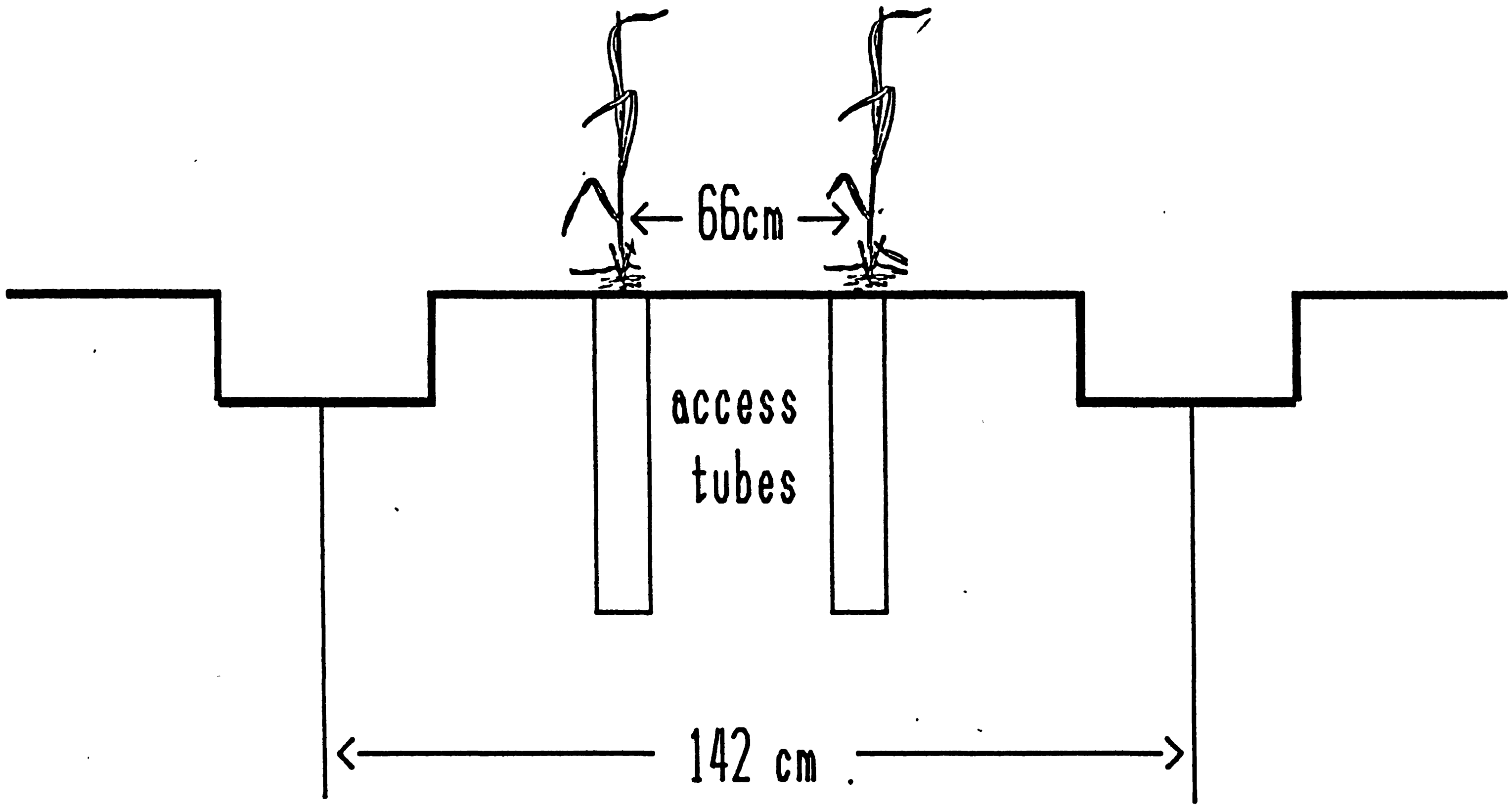

Fig. 2. Field geometry and neutron probe access tube locations at the Goodwell field site.

sensors were used to collect data on several meteorological components, which included those required for the execution of the SORGF model. Data was present for the entire growing season during 1984. Data collection during 1985 did not begin until July 10. The temperature and rainfall data for the early 1985 growing season was obtained from other climatological records collected at the Goodwell station. Solar radiation data for the same period was reconstructed from readings taken with a Eppley black and white pyranometer[2], Model 8-48, also located at the Goodwell station.

Calibration of the Model

As noted previously, certain parameters within the SORGF model must be calibrated to the specific site in question if reasonable simulation results are to be obtained. Major emphasis was placed on factors which would affect soil water balance calculations. The maximum value of extractable soil water, UL, was quantified for the Goodwell site using a technique similar to that described by Ritchie et al. (1976) and Ritchie (1981). He concluded that the value of UL was the quantity of water held between a wet upper limit and a dryer lower limit. The upper limit determination involves measurements of soil water content following a heavy rain or irrigation to depths about 25 cm below the root zone. The soil profile should be well

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[2] Eppley Laboratory Inc.

drained and wet to its upper limit of water holding capacity. The lower limit determination involves water content measurements to the same depth when plants with complete root development cease to extract water from the soil profile.

The upper limit was determined by analyzing soil water content data collected one to two days after the first two EFI events of the 1984 and 1985 growing seasons (Tsegaye, 1986). These specific events were selected so the estimate would not be distorted by large soil water losses from surface evaporation and plant extraction. The first soil moisture observation of the season was also used since the profile had received moisture from rainfall prior to the reading date. The total quantity of water in the profile on dates considered for the estimate of the upper limit are presented in Table 4. The data for each date and treatment is the average reading from six access tube locations. Several observation dates produced unusually high soil water levels, which probably resulted from inadequate drainage time following the date of the irrigation. However, the majority of the reading dates yielded soil water levels between 55 and 56 cm. Since the data within this interval seemed to be the most representative of the profile following an EFI event, the upper limit was determined as 55.5 cm, the mean of these values.

The value of the lower limit was estimated by using soil water data collected during the 1984 growing season

TABLE 4.

Total soil water in the profile on dates considered for upper limit determination during the 1984 and 1985 growing season at Goodwell, OK.

Calendar Day	Year	Treatment EFI-14	EFI-21
		---------- cm	--------
169	84	55.1	57.3
178	84	56.2	58.6
191	84	55.7	55.2
170	85	51.8	55.8
179	85	55.7	58.4
194	85	55.5	52.3

from a dryland study located adjacent to the above site (Tsegaye, 1986). Since no water content data was available below the 120 cm depth for 1984, the soil water content from 120 cm to 180 cm was assumed to be equal to that at the 120 cm depth. Observations from two access tube locations were available. This site received water only in the form of rainfall, and the grain sorghum plants exhibited considerable water stress during July and August. Examination of successive water content profiles during these periods provided a good estimate of the soil water content in the profile when the plants ceased to extract water (Fig. 3). The value of the lower limit was determined as 29.6 cm. The typical soil water content values in the profile for both the upper and lower limits are given in Fig. 4. By subtraction, the value of UL was found to be 25.9 cm when a 155 cm root zone is assumed.

The soil characteristics of a given location also have an effect on the rate of surface evaporation from that particular soil. The SORGF model makes allowances for these characteristics by defining the critical point between Stage 1 and Stage 2 evaporation, U, and assigning a constant, β, which effects the determination of Stage 2 evaporation in equation [8]. The determination of U was performed in the laboratory using surface soil collected from the Goodwell site. A sample of soil was first crushed and then passed through a 2 mm sieve to remove small stones and crop residue. The soil was then packed into an acrylic

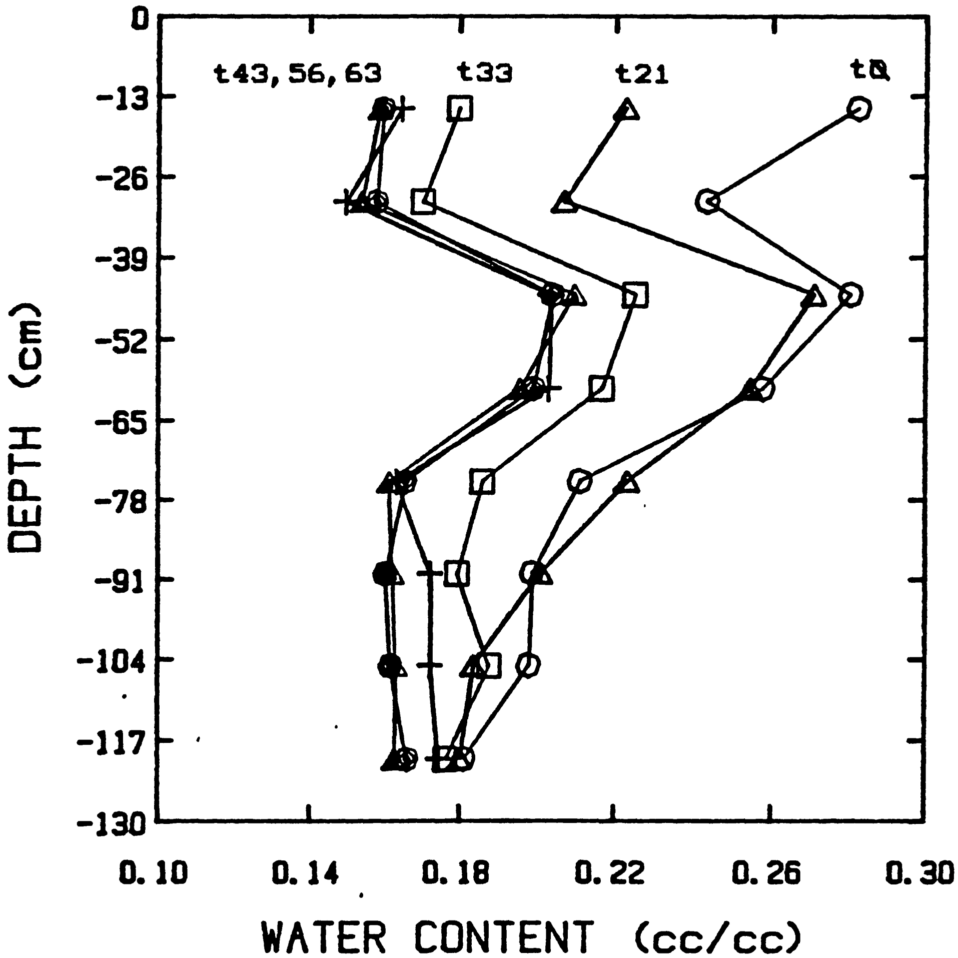

Fig. 3. Successive soil water content profiles from a dryland study at Goodwell, OK., where ti represents days after the first measurement.

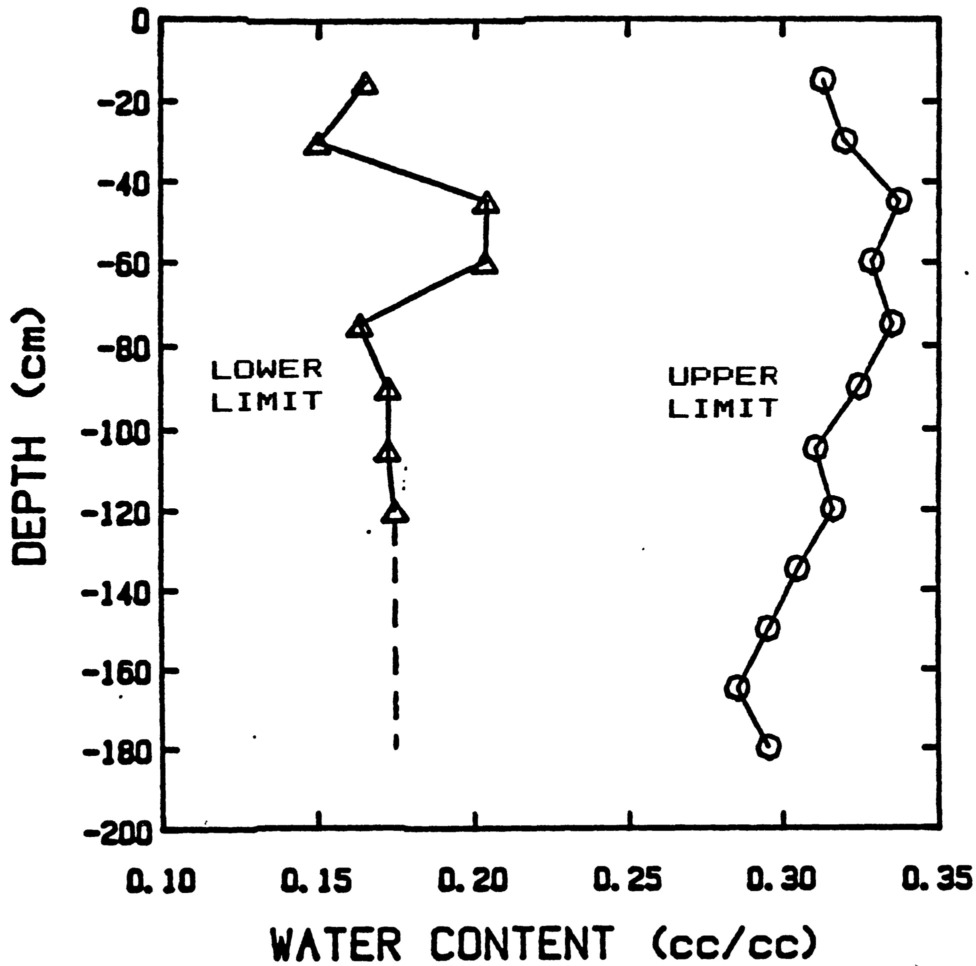

Fig. 4. Soil water content distribution with depth at the upper and lower limit for a Richfield clay loam at Goodwell, OK.

cylinder, 9 cm in height and 7 cm in diameter. The column was then saturated with distilled water, covered to prevent surface evaporation, and left for 24 hours to allow for drainage and redistribution. The sample was then weighed and placed under high evaporative conditions. Heat lamps were used to add thermal energy while a fan moved air across the surface of the sample. A heat shield was used which allowed heating of the soil surface only, and an O-ring was placed on the soil surface at the cylinder boundary to prevent air movement between the cylinder wall and the soil column. Periodically the sample was weighed to determine the evaporation rate over the time period since the last weighing. As the soil surface dried, the evaporation rate eventually decreased, allowing for the estimation of U. The experiment was repeated four times and produced estimates of U between 1.11 cm and 1.22 cm with a mean of 1.18 cm. Since the objective was to estimate U, and not make a precise determination, a value of 1.2 cm was assigned to U for simulation purposes.

Data presented by Ritchie (1972) summarized estimates of U and β at 4 different locations (Table 5). Inspection of this data indicated that a strong linear relationship may exist between U and β. This suggests that once an estimate of one parameter is obtained, a reasonable estimate of the other parameter is possible. Linear regression analysis produced an equation to estimate the value of β as a function of U

TABLE 5.

Upper limit of Stage 1 cumulative evaporation, U, and Stage 2 evaporation coefficient, ß, for 4 soil types.

Soil Type	U cm	ß $cm/day^{1/2}$	Reference
Adelanto clay loam	1.2	0.508	van Bavel et al.,(1968)
Yolo loam	0.9	0.404	LaRue et al., (1968)
Houston black clay	0.6	0.350	Ritchie et al., (1972)
Plainfield sand	0.6	0.344	Black et al. (1969)

$$\beta = 0.27(U) + 0.176 \qquad (R^2 = 0.976) \tag{9}$$

where the units of the slope and intercept are, $cm^2/t^{1/2}$ and $cm/t^{1/2}$, respectively. Fig. 5 plots β vs U using the data from Table 5 along with the corresponding regression line from equation [9]. Using the value of U previously determined in the laboratory, equation [9] was used to make an estimate of β for the simulation site (β=0.5cm/$t^{1/2}$). It should be noted that the value of U determined for the Goodwell sample corresponds to that of the Adelanto clay loam, a soil of the same texture. Once the values of UL, U, and β had been determined, the soil water balance portion of the SORGF model was assumed to be calibrated for a Richfield clay loam at Goodwell,OK.

WSFI Modifications

The application of water to the field in a nonhomogeneous fashion, such as wide spaced furrow irrigation, necessitated modification of certain other portions of the model. Stone et al. (1979) suggested that the benefits of WSFI resulted from reduced evaporation from the soil surface. This seems logical since during a WSFI event a portion of the field surface remains dry, where as during EFI the entire surface of the field is nearly saturated. This logic led to a new technique of accounting for evaporative losses after a nonhomogeneous furrow irrigation

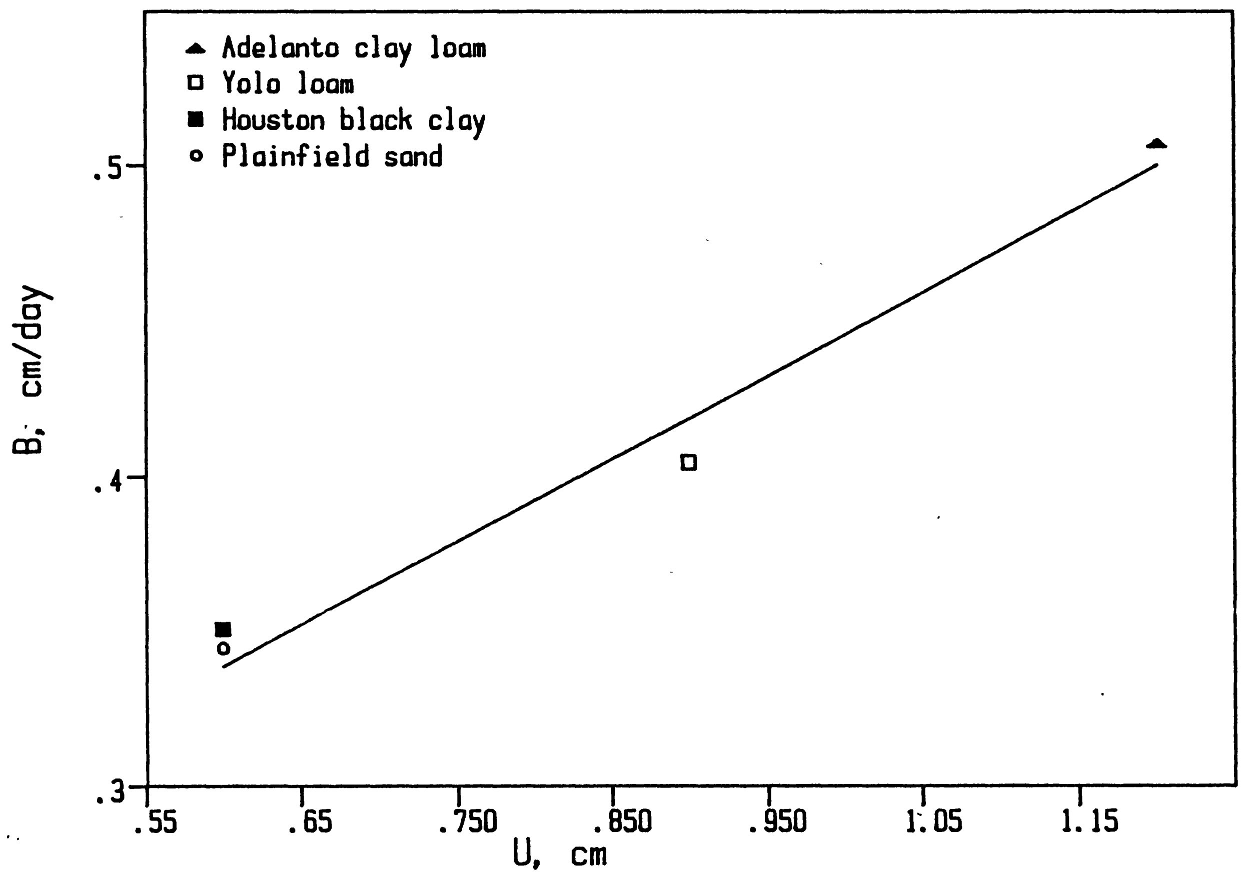

Fig. 5. Relationship between Stage 2 drying coefficient, ß, and the upper limit of Stage 1 cumulative evaporation, U, for four soil types.

event. To cope with this problem the field surface was divided into three distinct regions (Fig. 6). Region 1, located adjacent to the wetted furrow would be expected to have a high evaporation rate. Region 2 would also have a wet soil surface but a somewhat drier subsoil, thus evaporation from this region would be slightly less than Region 1. Region 3, adjacent to the dry furrow has a dry soil surface and exhibits a much lower soil evaporation rate. After a WSFI irrigation event the evaporative losses from each region were calculated in the following manner. Region 1 was allowed to stay in Stage 1 evaporation until the cumulative Stage 1 evaporation value reached the critical point, (U=1.2 cm), as reported earlier. However, Region 2 was allowed only 0.6 cm of Stage 1 evaporation since the surface of the soil in this region dried more quickly. Therefore, Region 2 exhibits Stage 1 drying for exactly one half the time as Region 1. Region 3 will be at some point in Stage 2 evaporation depending upon the previous drying cycle. Fig. 7 indicates where evaporation would begin for each region at time zero, immediately following a WSFI event. The numbered arrows correspond to the evaporative starting point of the the three regions. Once the evaporation rate from all three regions was determined, equation [10] was used to determine the average evaporation from the entire region, weighted according to the size of each evaporative region.

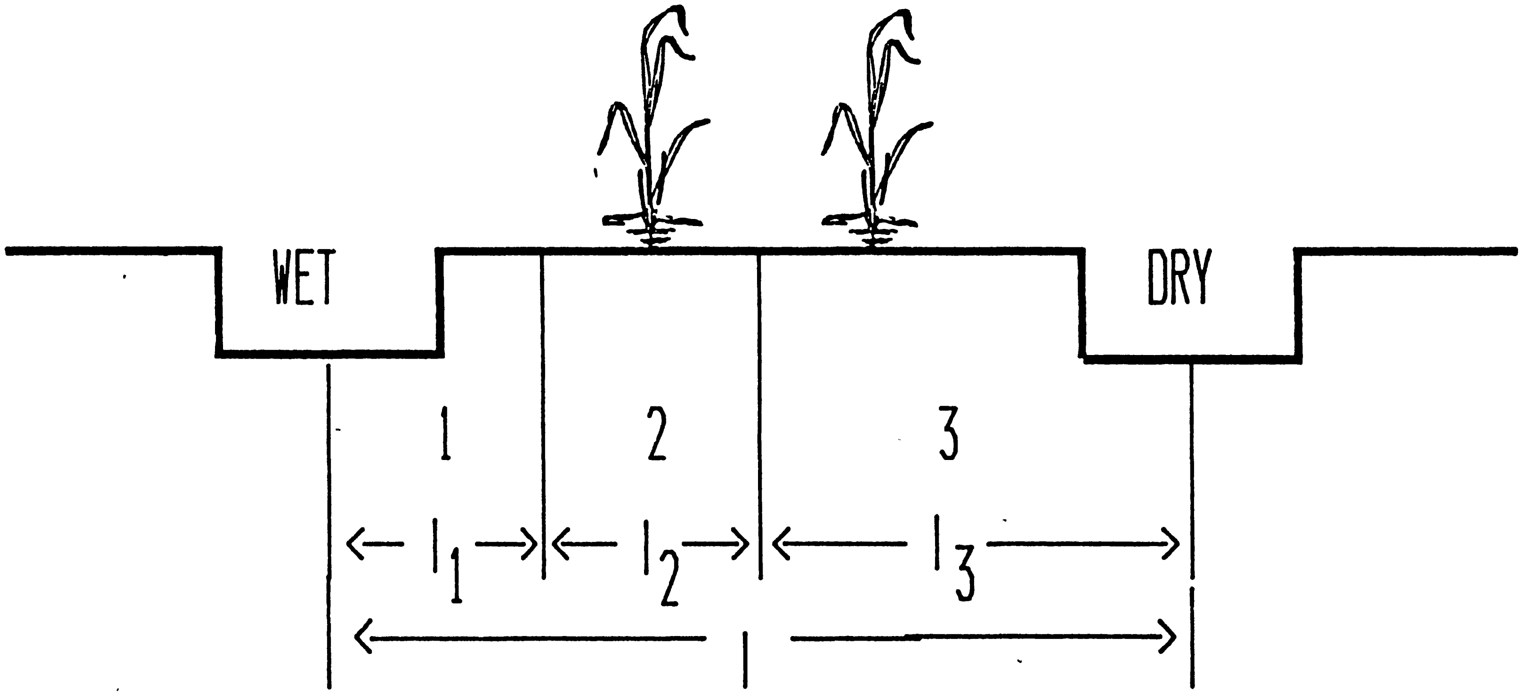

Fig. 6. Designation of the three regions of soil surface evaporation during a WSFI event.

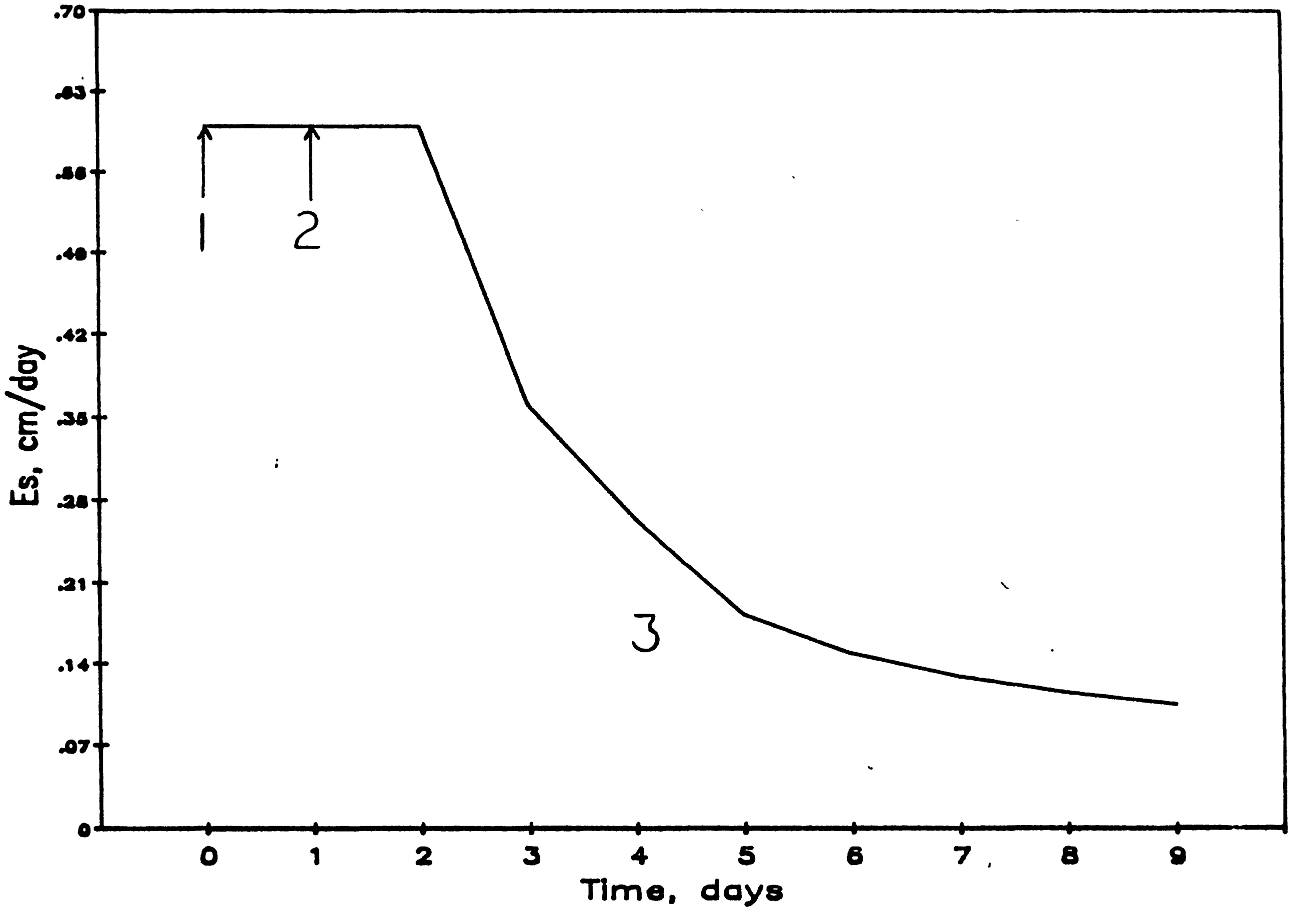

Fig. 7. Initial starting point for each evaporative region following a wide spaced furrow irrigation event.

$$Es = \frac{(Es' l_1 + Es'' l_2 + Es''' l_3)}{l} \qquad [10]$$

where;

Es' = daily evaporation from Region 1, cm/day
Es'' = daily evaporation from Region 2, cm/day
Es''' = daily evaporation from Region 3, cm/day
l_1 = distance assigned to Region 1, cm
l_2 = distance assigned to Region 2, cm
l_3 = distance assigned to Region 3, cm
l = total distance between furrows, cm

This average value of Es was then used to estimate the average quantity of extractable water over the entire region in equation [2]. The size of the surface area assigned to the three regions was determined from field observations which indicated that on the day of a WSFI event, the soil surface wetting front consistently reached a distance approximately half way between the two furrows. The field geometry of the Goodwell site led to the assignment of the region distances as follows;

l_1 = 33 cm
l_2 = 38 cm
l_3 = 71 cm
l = 142 cm

The size of the evaporative regions could be adjusted to fit other field situations depending on the distance between the furrows and the characteristics of surface wetting during a WSFI event.

This type of WSFI drying cycle is allowed to continue on a daily basis unless a large precipitation event occurs which completely saturates the profile. In this case the model immediately reverts back to the original SORGF evaporation theory for a homogeneous application of water described in chapter III. Two other criteria were defined to potentially deactivate the WSFI drying cycle. The first occurs the day before a WSFI event when the model is still in a WSFI drying cycle. In this case it was necessary to determine the average point in time of all three regions on the evaporation curve so that a initial evaporative rate for Region 3 could be determined for the upcoming WSFI event. That is, an estimate of the average drying state of Regions 1 and 2 must be determined since they will collectively become Region 3 after the forthcoming WSFI event. This was accomplished by taking a weighted average of the ΣEs_2 of all three regions based on the distances assigned to each region.

$$\Sigma Es_2 = \frac{(l_1 \Sigma Es_2' + l_2 \Sigma Es_2'' + l_3 \Sigma Es_3''')}{l} \qquad [11]$$

where;

$\Sigma Es_2'$ = cumulative Stage 2 evaporation, Region 1, cm
$\Sigma Es_2''$ = cumulative Stage 2 evaporation, Region 2, cm
$\Sigma Es_2'''$ = cumulative Stage 2 evaporation, Region 3, cm

All three regions were averaged since the differences in the evaporation rate between the three regions is very small when this criterion is met. Equation [7] was then used to solve for time such that, equation [8] could be used to calculate the evaporation rate from Region 3 after the WSFI event. The second criterion for exiting a WSFI drying cycle occurs when all three regions are in Stage 2 drying and the difference between the evaporation rate in

Region 1 and Region 3 is less than 10 percent. If this criterion is met, equation [11] is again used to calculate the average ΣEs_2 from all three regions and the Es calculations are made assuming equal evaporation rates over the entire region.

A second but equally important modification was made concerning an adjustment to the maximum amount of extractable soil water held in the root zone, UL, on the day of a WSFI event. An estimate of UL is a required model input in equation [3] regardless of the type of irrigation used. As mentioned earlier, the value for UL under EFI conditions was found to be 25.9 cm by using soil water content measurements from the experimental site. However, the average value of UL during WSFI must be some degree less than the value associated with EFI, since a dry region exists near the non-irrigated furrow.

Soil water content data from the WSFI treatments at the Goodwell location (Tsegaye, 1986) was used to estimate the upper limit during a WSFI event. However, the estimates of the upper limit after a WSFI are composed of average readings from tubes located adjacent to a wet furrow, and other tubes located adjacent to a dry furrow. Thus, the average of the readings from the two tube groups is representative of the upper limit for a hypothetical plant centered between the two tubes. Depicting the upper limit under WSFI in this manner appears valid since no visual differences between plants in different rows was reported.

Fig. 8 demonstrates typical differences in the soil water content profiles adjacent to the wet and dry furrows for two WSFI events in 1985. The profiles with a lower water content near the surface are the average of tubes located next to the non-irrigated furrow, while profiles with a wet upper surface represent tubes adjacent to the irrigated furrows, on the same reading date. The observation dates used for the upper limit determination for an WSFI event were selected using the same criteria as used for an EFI event. However, plots of total soil water vs time were used to estimate the soil water level on the actual date of irrigation by extrapolation. Special attention was given to eliminate irrigation dates immediately following a rainfall event, since this fact would distort the upper limit of the dry region. Table 6 shows the quantity of soil water present in the regions adjacent to the irrigated and dry furrows for the dates used in the upper limit determination. Each soil water value is the average of readings from three access tube locations. The upper limit for the region adjacent to the wet furrow appeared to be the same as that used for a EFI event. The upper limit for this region was determined as 55.5 cm. However, the upper limit for the region next to the non-irrigated furrow was 4 to 6 cm less than observed during an EFI event, approximately 50.5 cm. The average upper limit for the two regions was set at 53.0 cm or 2.5 cm less than that used during a EFI event. The lower limit for the region was set

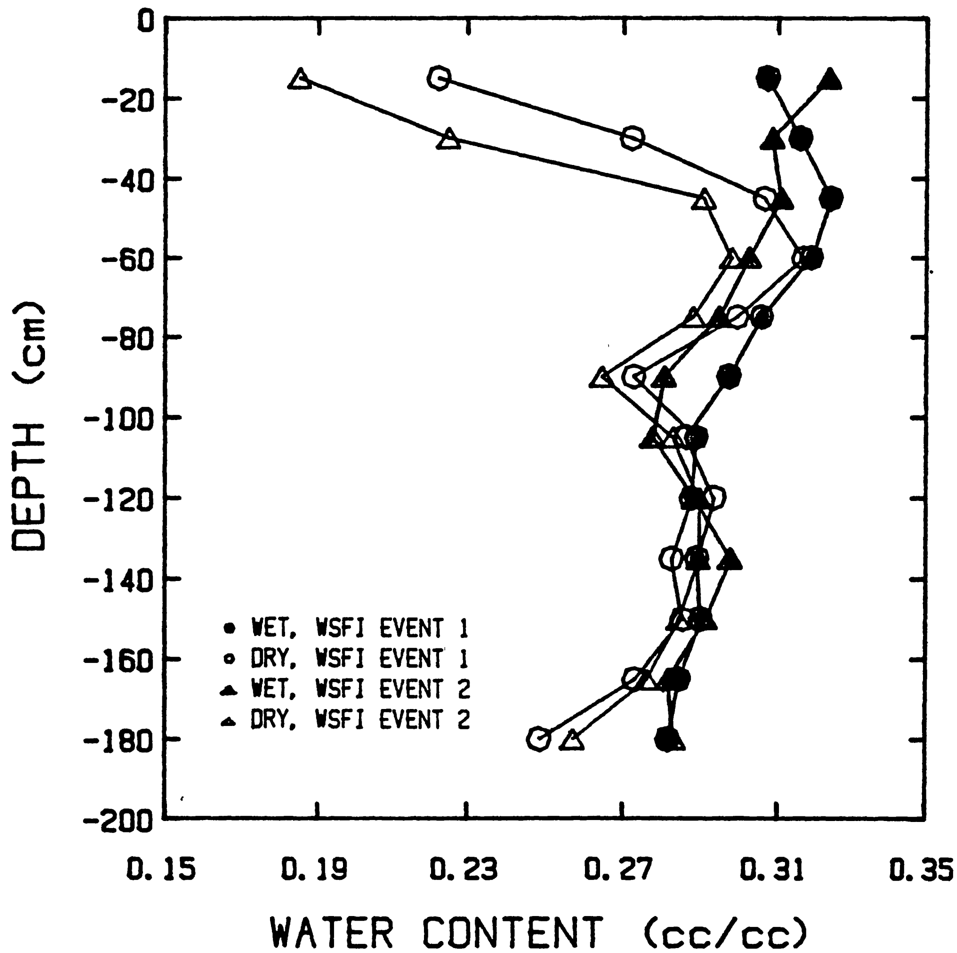

Fig. 8. Soil water content distribution with depth measured from tubes adjacent to the wet and dry furrows after a WSFI event (Tsegaye, 1986).

TABLE 6.

Soil water observations used for the upper limit determination during a WSFI event.

Irrigation Interval (days)	Date of Irrigation	Year	Total Soil Water: Adjacent to Irrigated Furrow	Total Soil Water: Adjacent to Dry Furrow
			-------- cm	---------
7	178	84	58.3	52.6
7	188	84	57.7	52.1
10	178	84	55.3	50.5
10	192	84	52.5	51.2
7	176	85	56.0	51.0
7	183	85	55.2	51.5
7	190	85	55.6	49.0
10	182	85	54.2	50.5

to the same value determined earlier from the dryland study, since the soil water level at which the plants cease to extract water is a function of physiology, not the method of irrigation. Thus, the maximum value of extractable water allowed on the day of an WSFI event, UL_w, was 23.5 cm, or 2.5 cm less than that for an EFI event (UL=25.9). However, if a large rainfall event occurred the value of S_w was allowed to reach 25.9 cm. The value of UL_w was used to replace the value of UL in equation [3] during a WSFI event. All of the above modifications for a WSFI event were applied within the SOLWAT module of the SORGF source code (Appendix A), and this version of the model was named SORGF/WS. A simplified flow diagram of the modified SOLWAT module exists in Fig. 9.

Computing Methods and Source Code Verification

The original FORTRAN WATFIVE source code for the SORGF model was presented by Maas and Arkin (1978). This code was translated into the Turbo Pascal[3] programming language for research conducted by Hornbaker (1985). This allowed for program execution on a microcomputer, specifically an IBM-PC[4] or compatible. Before research concerning WSFI was conducted, the Pascal source code was tested for structural integrity by executing the model using a given set of climatic and input data provided by the original

[3] Borland International Inc.
[4] International Business Machines Corporation

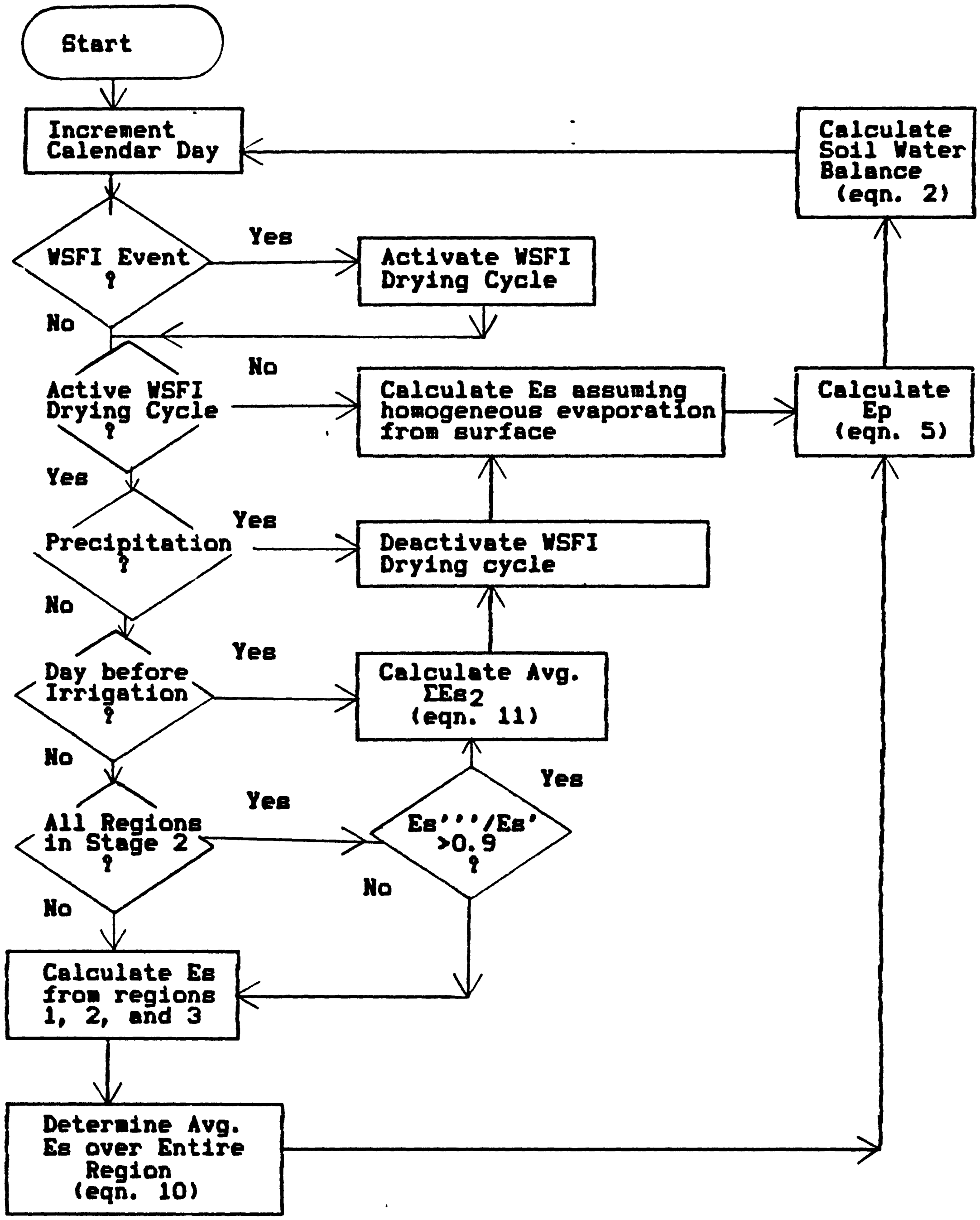

Fig. 9. Flow diagram of the modified SOLWAT procedure for wide spaced furrow irrigation.

developers. The results of the simulation were then compared to the documented results. After several small errors were corrected, complete agreement was achieved. The source code was modified to produce output suitable for the research project, and a graphics program was also added which plotted the response of specific variables over the growing season. All results reported concerning this research were obtained by executing the Pascal version of the model on a IBM-PC[5] or Corona PPC-400[6] micro-computer. Both computers were equipped with an Intel 8087 math-processor[7] which provided greater numeric accuracy and increased computing speed. The 8087 chip provided 15 digit accuracy, while simulating one complete growing season in 2 to 3 minutes.

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[5] Ibid.
[6] Corona Data Systems, Inc.
[7] Intel Corporation

CHAPTER V

RESULTS AND DISCUSSION

Model Configuration and Execution

The model was used to simulate the 1984 and 1985 growing seasons at Goodwell, OK, with the intention to compare the results to data collected from experiments conducted by Stone (1985) and Tsegaye (1986). Given that four treatments were used over two growing seasons, eight simulations were executed (Table 3). EFI and WSFI were each simulated four times. In addition to the modifications for WSFI in SORGF/WS, another change was made to both versions of the model concerning the calculation of albedo in procedure EVAP. This modification is documented in Appendix B. Before the simulation of the Goodwell, OK, location, all calibrated constants determined for the location were inserted into the Pascal code. The required model inputs for the eight simulations were set according to the field characteristics used during the 1984 and 1985 growing season. Appendix C contains all the required SORGF inputs used for the 1984 and 1985 growing season, along with their corresponding variable names present in the SORGF code. Simulations within a given year were conducted using the corresponding climatic data collected at the Goodwell location (Appendix D). The date and quantity of each irrigation application is presented for all treatments in Appendix E. All simulations began at the date of planting and terminated at physiological maturity. Feedback was not used at any point in the growing season. That is, daily parameters within the model were never adjusted using data provided from field observations. Thus, errors within any facet of the model could accumulate as the season progressed.

Simulation of the Soil Water Balance

The ability of the model to simulate the soil water balance over the growing season was an important aspect of the modeled performance. Large errors in soil water balance calculations will have an effect on almost all other determinations within the model, including rate of development and grain yield. Simulated daily soil water values were compared to the observed soil water levels for all treatment combinations. The simulated soil water level, Sw, was assumed to be equal to UL on the date of planting. However, the first available soil water data from the field occurred two and four weeks after the date of planting for 1984 and 1985, respectively. Thus, the model was allowed to simulate soil water changes for some time before the first comparison was made. Plots of simulated and observed daily soil water levels were constructed to indicate the precision of the model over the growing season. Each observed data point is the mean of readings from six access tube locations under the same treatment. It should be noted that the model returns soil water values on a daily basis, but modeled results were plotted only on the dates in which observed soil water was available. This format made the comparison of simulated and observed values more clear, since both plots had the same configuration. The same scale was used for all plots to allow for direct comparison. Figures 10 through 13 show the modeled and simulated soil water levels for the EFI treatments over both growing seasons using the calibrated SORGF model. Figure (a) of the above plots is the simulated and observed soil water level vs time, while Figure (b) is simply the difference between the simulated and observed values, or the soil water residual. Positive residuals represent periods when the model overestimated soil water levels, while negative values represent underestimates.

The graphical results of the EFI simulations indicated various degrees of precision depending on the year and treatment combination. For example, the 1984 EFI-14 treatment (Fig. 10) shows excellent agreement between simulated and observed soil water levels for the entire growing season. The largest error of 3.23 cm, occurs on the last day of comparison. The second largest error on calendar day 222 was only 1.95 cm or 8.3 percent. However, simulation of the same treatment for 1985 (Fig. 12) was

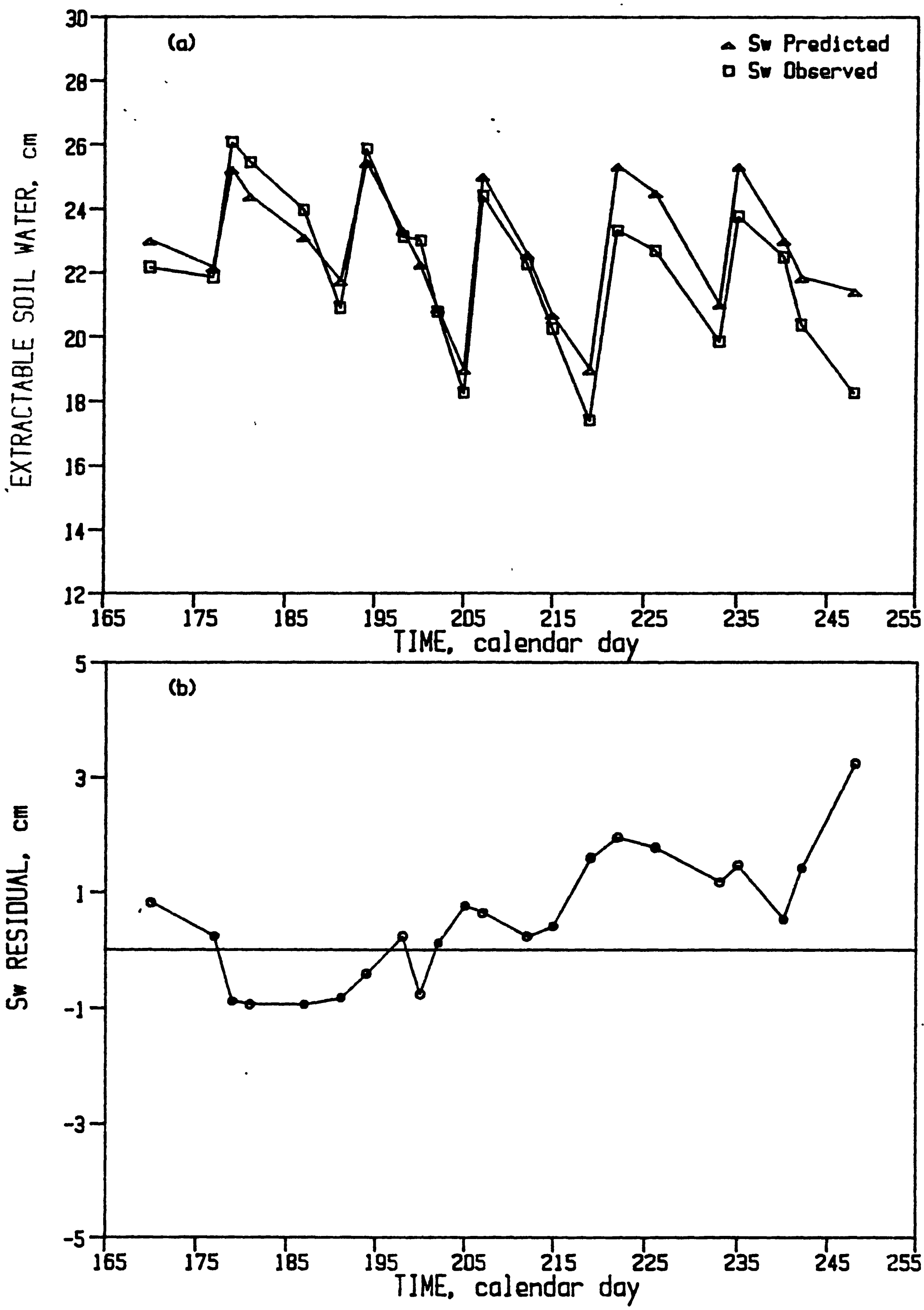

Fig. 10. Soil water balance simulation of trt. EFI-14, 1984 a) simulated and observed extractable soil water vs time, and b) soil water residual vs time.

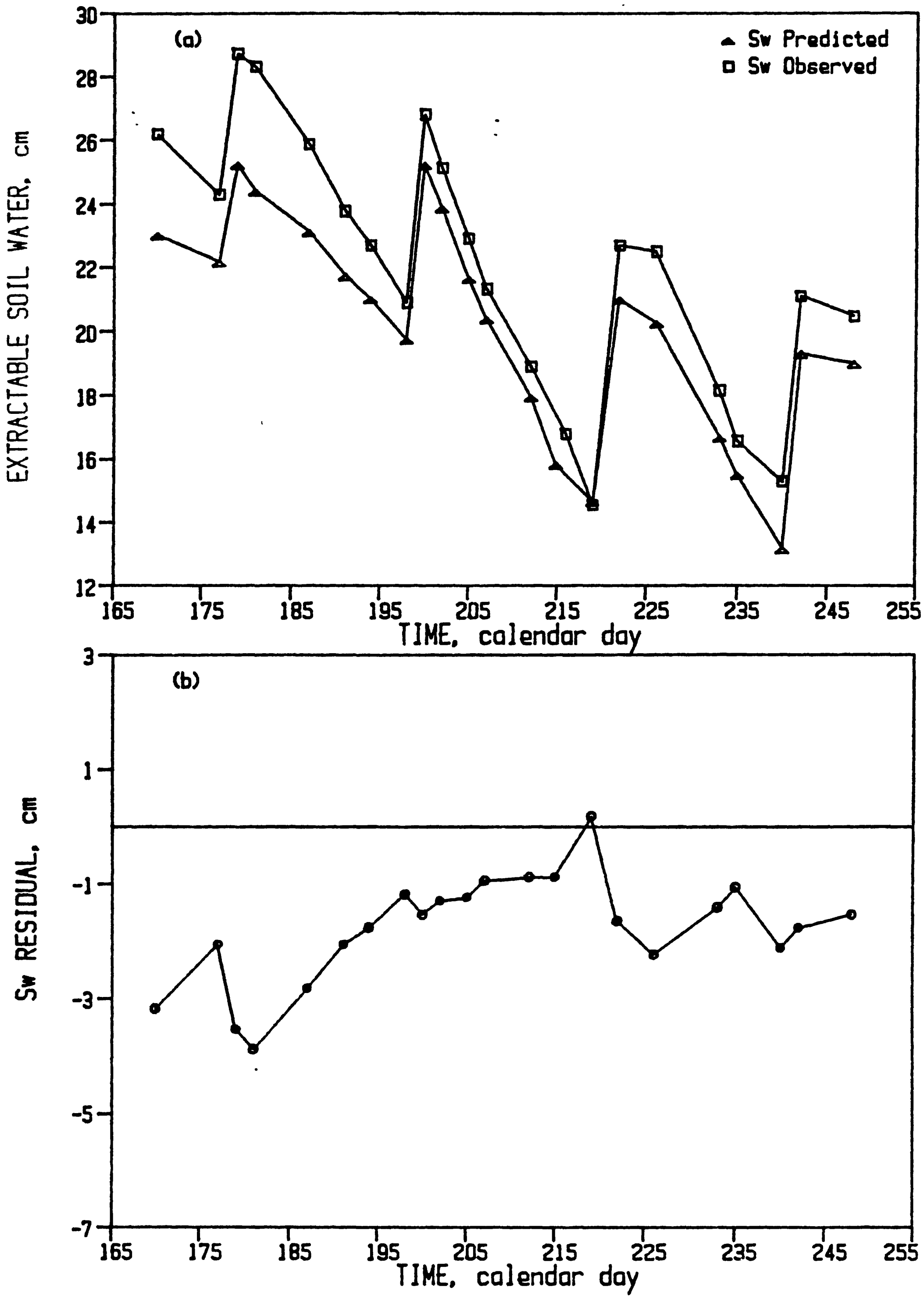

Fig. 11. Soil water balance simulation of trt EFI-21, 1984 a) simulated and observed extractable soil water vs time, and b) soil water residual vs time.

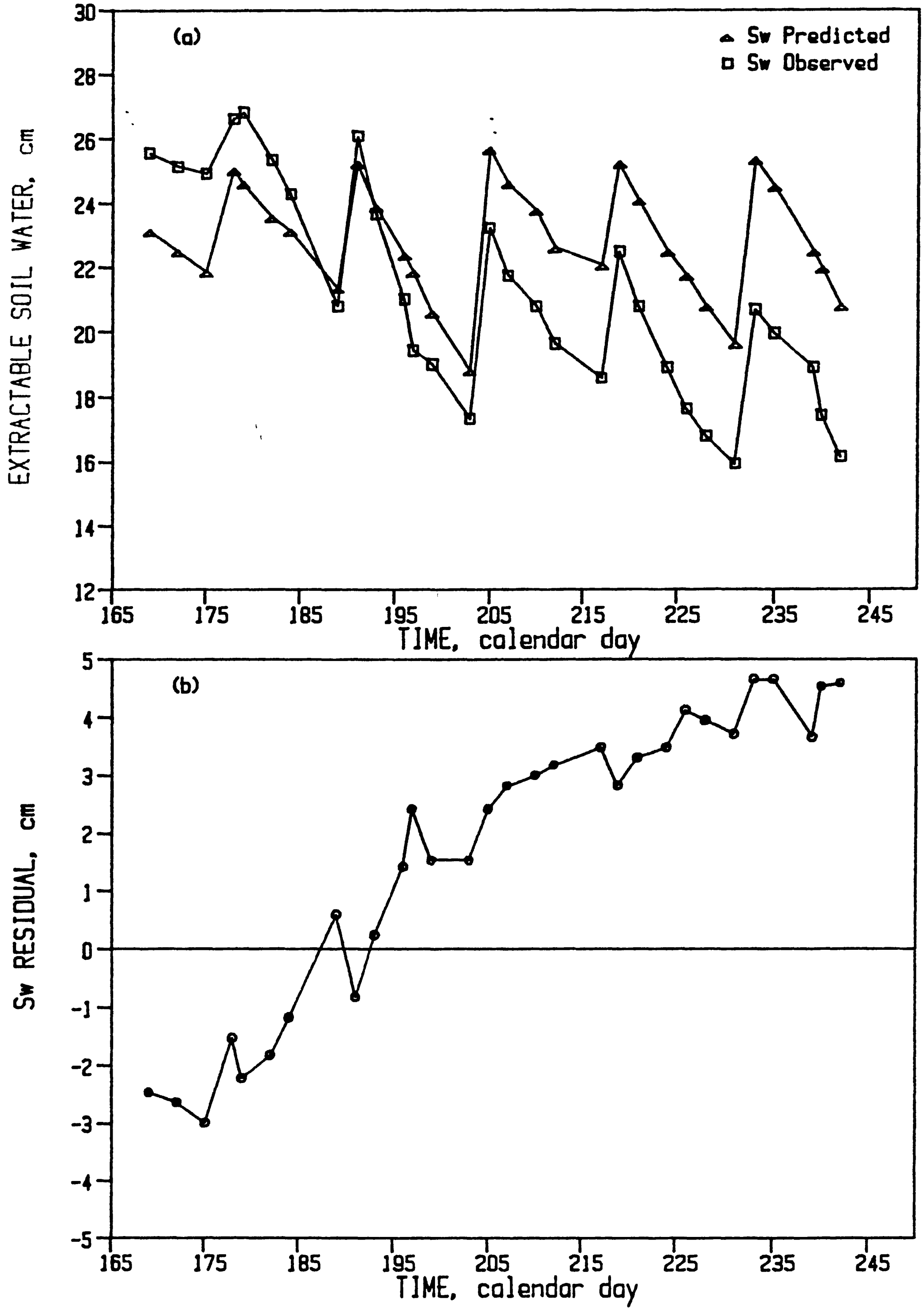

Fig. 12. Soil water balance simulation of trt EFI-14, 1985 a) simulated and observed extractable soil water vs time, and b) soil water residual vs time.

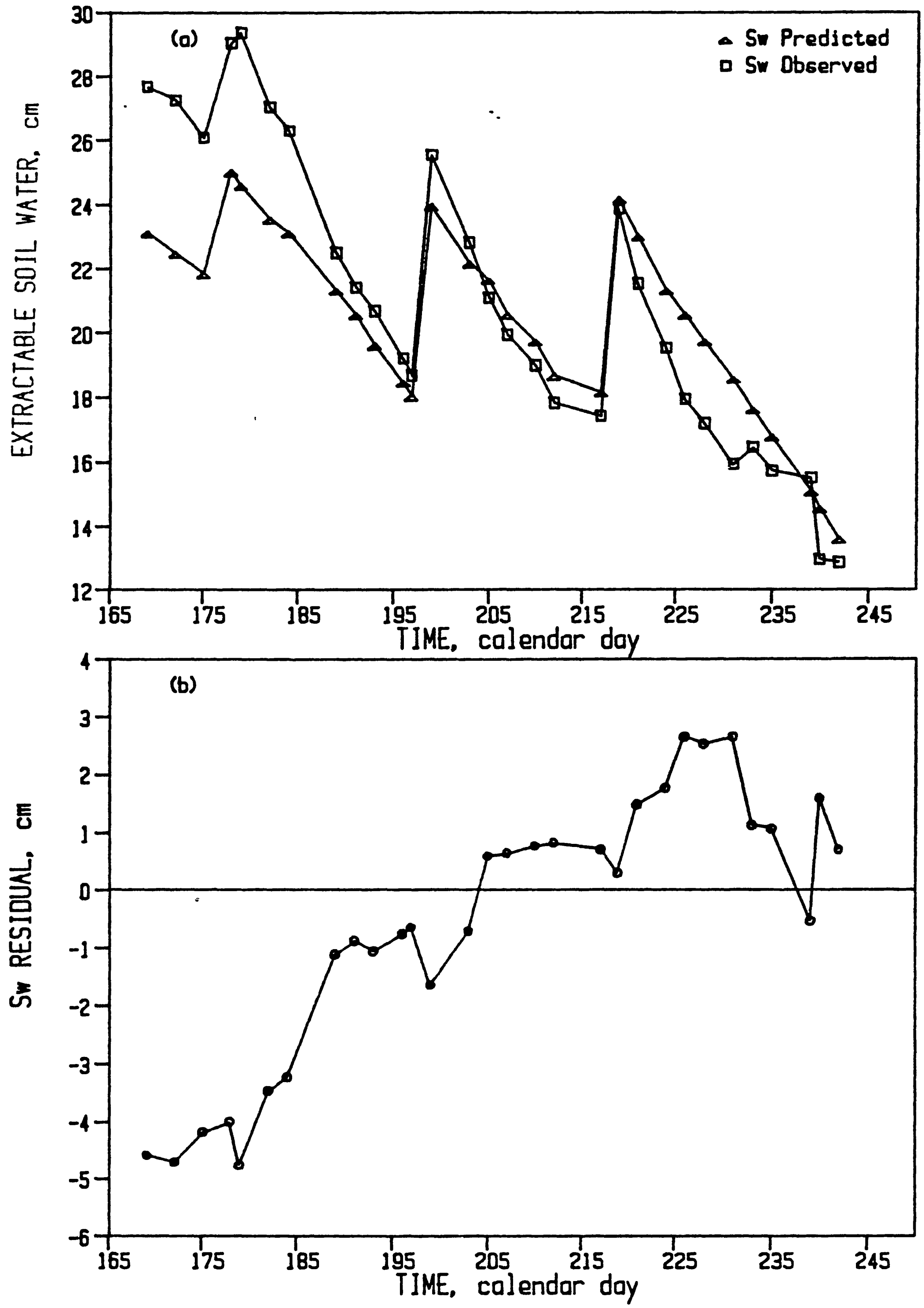

Fig. 13. Soil water balance simulation of trt EFI-21, 1985 a) simulated and observed extractable soil water vs time, and b) soil water residual vs time.

characterized by overestimates of the soil water level late in the growing season. It appears that the model returns the soil water level to the upper limit on the date of an irrigation, while the observed data indicated a gradual decrease in soil water over the growing season. Figures 14 through 17 present the same graphical output for the WSFI treatments, where the modified SORGF/WS model was used. Again, a variety of results were obtained from simulations under different year and treatment combinations. While this type of analysis is difficult to quantify, it shows that the model approximated changes in the soil water balance reasonably well in all eight cases. Also of great interest is the fact that the modified SORGF/WS model was capable of following the rapidly changing soil water levels under WSFI in most cases. This indicated that the theory behind the WSFI modifications must constitute a reasonable approach to a nonhomogeneous application of water. While this type of graphical analysis proved useful, it did not serve well to quantify the overall precision of the model under different year and treatment combinations. To cope with this problem two 'statistics' were used to estimate the average precision of the simulations over the growing season. The first statistic used was the mean of the absolute value of the soil water residuals over the entire growing season.

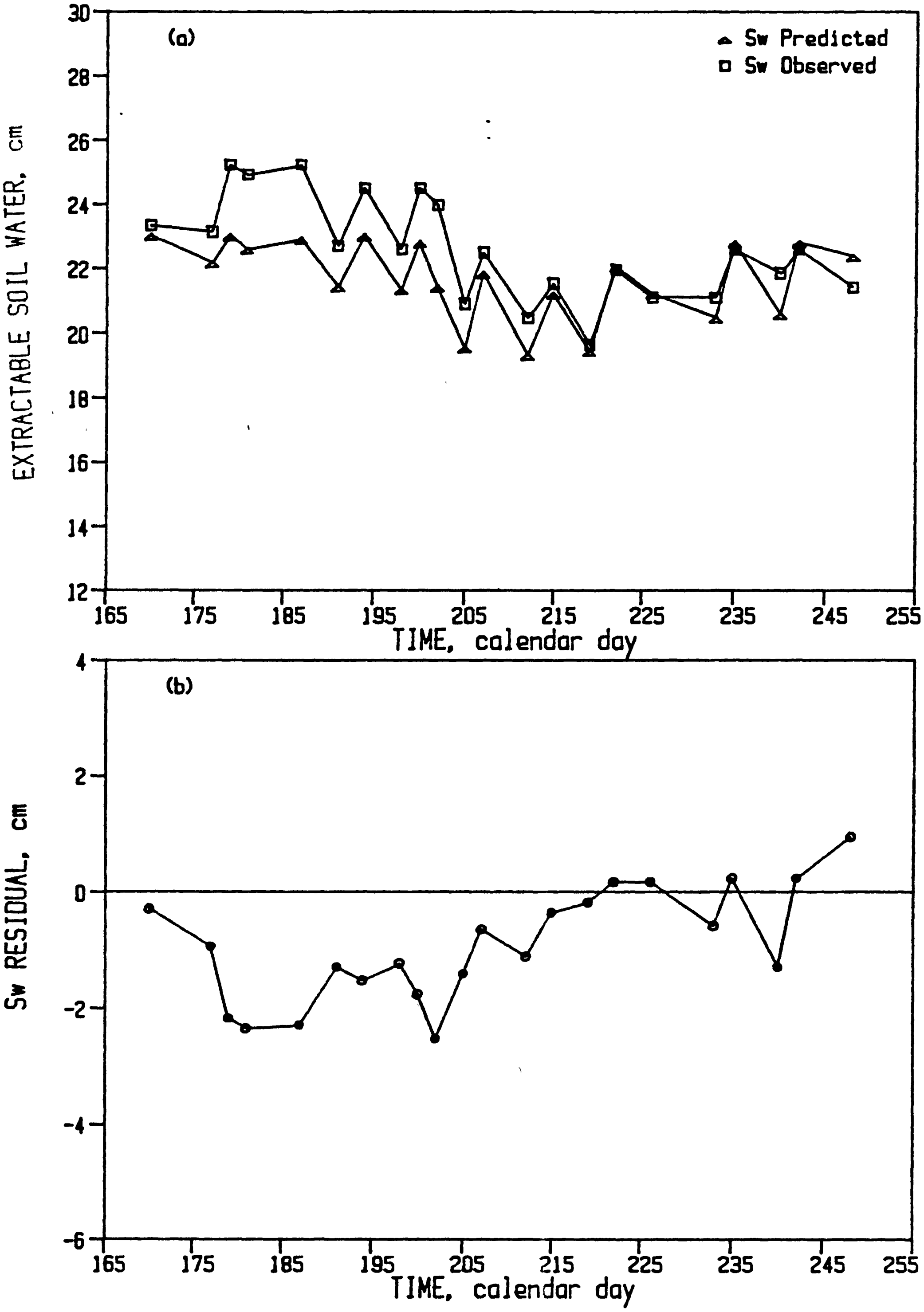

Fig. 14. Soil water balance simulation of trt WSFI-7, 1984 a) simulated and observed extractable soil water vs time, and b) soil water residual vs time.

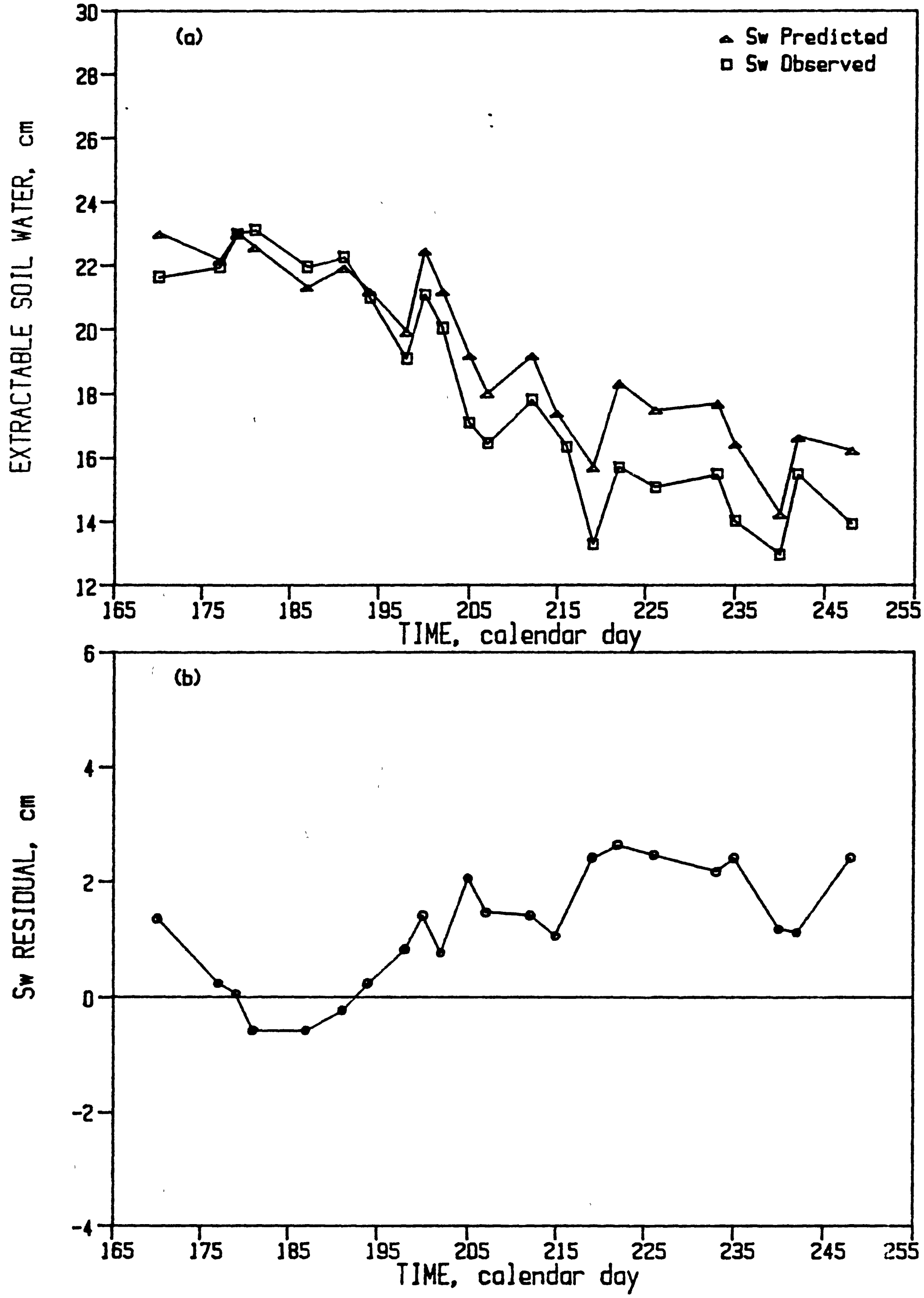

Fig. 15. Soil water balance simulation of trt. WSFI-10.5, 1984 a) simulated and observed extractable soil water vs time, and b) soil water residual vs time.

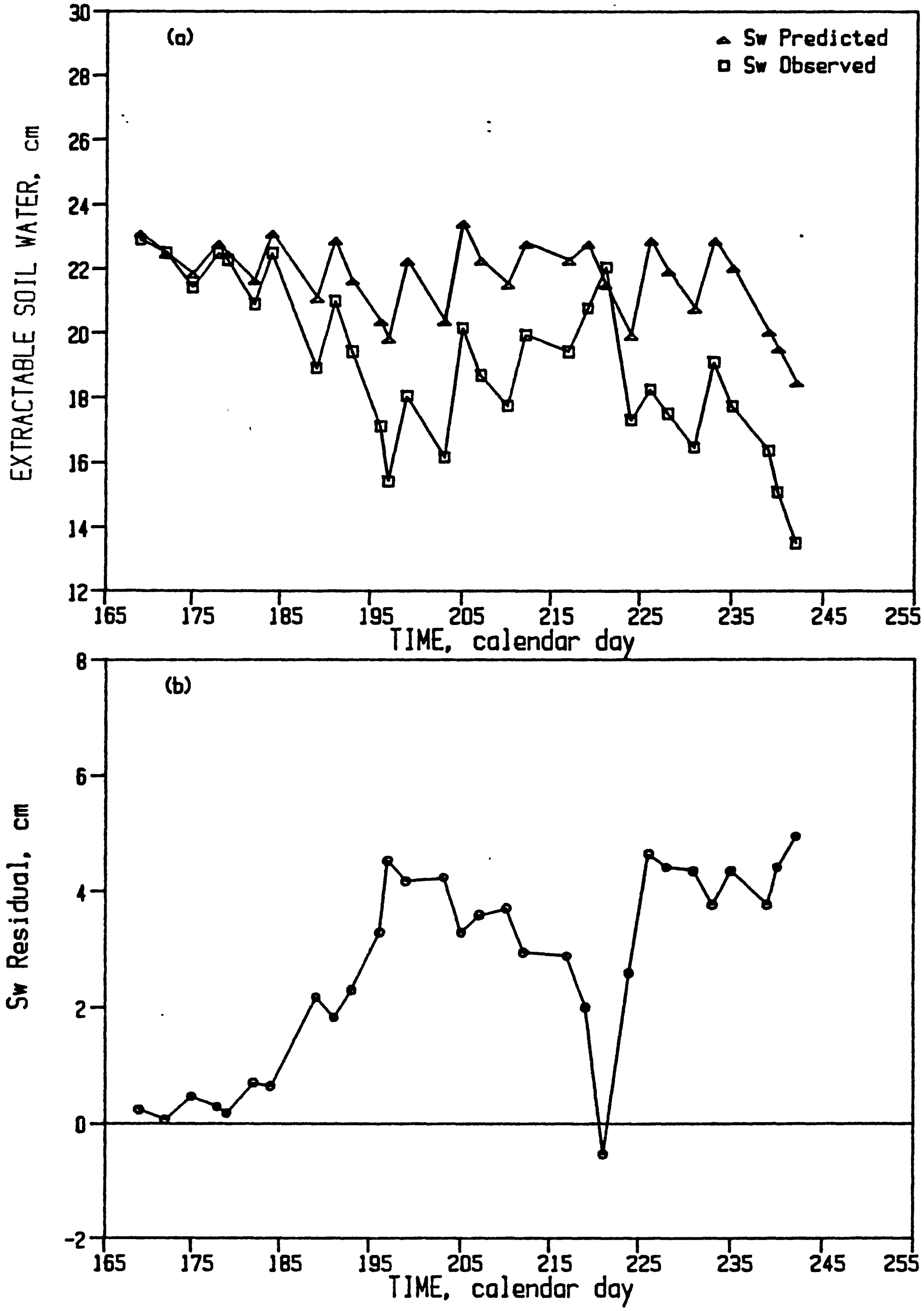

Fig. 16. Soil water balance simulation of trt WSFI-7, 1985 a) simulated and observed extractable soil water vs time, and b) soil water residual vs time.

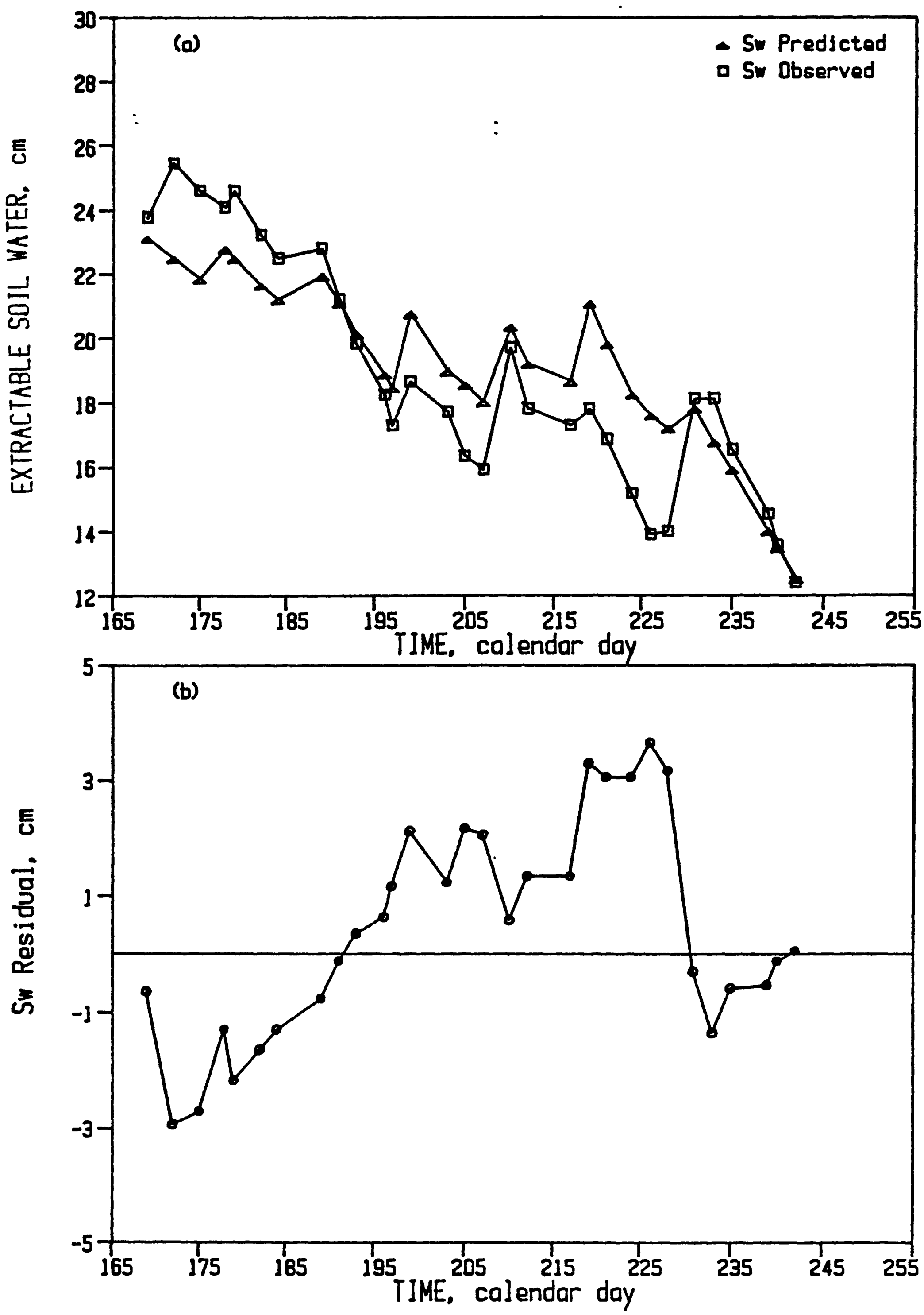

Fig. 17. Soil water balance simulation of trt WSFI-10.5, 1985 a) simulated and observed extractable soil water vs time, and b) soil water residual vs time.

$$SwRes = \Sigma\left(\left|\frac{SwPre - SwObs}{n}\right|\right) \qquad [12]$$

where;

SwPre = predicted soil water value, cm
SwObs = observed soil water value, cm
n = number of observations

This statistic represents the average difference between the simulated and observed soil water values on the dates that soil water data was available. Table 7 presents this statistic for all treatments in 1984 and 1985. These same values can be represented in terms of percent error by dividing by the average observed soil water level over the growing season (Table 8).

The results in Tables 7 and 8 indicate that all of the simulations for the 1984 growing season were of higher quality than those of the 1985 growing season. A review of the meteorological totals for both growing seasons did not indicate obvious climatic differences between years. However, the evaporative demand was somewhat greater in 1985 than 1984. Table 9 shows the simulated total ET for all treatments in 1984 and 1985. This result is consistent with that of Tsegaye (1986) who also reported greater net soil water extraction in 1985 than 1984 from analysis of neutron probe data at the same location (Table 10). Thus, the SORGF model may have difficulty accounting for the evaporative losses under high ET conditions. As mentioned earlier the model does not consider daily wind movement when making potential evaporation estimates, and may

TABLE 7.

Average soil water residual for all treatments simulated over the 1984 and 1985 growing season at Goodwell, OK.

Method of Irrigation	Irrigation Frequency (days)			
	1984		1985	
	7 & 14	10.5 & 21	7 & 14	10.5 & 21
EFI	0.97	1.78	2.72	1.84
WSFI	1.08	1.33	2.71	1.53

TABLE 8.

Average percent error between observed and simulated soil water levels for all treatments used over the 1984 and 1985 growing seasons.

Method of Irrigation	Irrigation Frequency (days)			
	1984		1985	
	7 & 14	10.5 & 21	7 & 14	10.5 & 21
EFI	4.4	8.1	12.9	8.8
WSFI	4.8	7.3	14.2	8.2

TABLE 9.

Simulated cumulative ET by treatment over the 1984 and 1985 growing season.

Treatment	Year 1984	Year 1985
	---------- cm	---------
EFI - 14	44.40	46.61
WSFI - 7	43.45	45.67
EFI - 21	42.99	44.54
WSFI - 10.5	42.49	44.56

TABLE 10.

Net soil water extraction for 1984 and 1985 growing season.[1]

Treatment	Year 1984	Year 1985
	---------- cm	---------
EFI - 14	30	39
WSFI - 7	29	38
EFI - 21	28	37
WSFI - 10.5	27	31

[1] (Tsegaye, 1986)

underestimate ET during windy conditions. It should be noted that rainfall during 1984 occurred in small quantities throughout the growing season, while 1985 was characterized by several large precipitation events near the beginning and end of the growing season. Thus, large rainfall events may also cause errors in soil water balance calculations. However, the plots used at the Goodwell location were level and bordered, which prevented unaccounted losses in the form of runoff. A final possibility for the differences in daily soil water accuracy between years is the improper simulation of plant growth rate in 1985. The 1984 simulation predicted anthesis on calendar day 224, while field notes indicated half bloom on day 219, a difference of only five days. However, anthesis was predicted on calendar day 217 in 1985, while field observations indicated anthesis on day 204, 13 days earlier. Thus, differences in the simulated and observed plant canopies could have resulted in different evaporation rates, giving rise to reduced precision in soil water balance calculations in 1985.

At high irrigation frequencies the EFI simulations had greater precision than did the WSFI simulations, while at low irrigation frequencies the opposite held true. This may indicate reduced precision of the SORGF/WS model at high irrigation frequencies under WSFI. However, the same comparison may indicate reduced precision of the original SORGF model at low irrigation frequencies under EFI conditions. Since the magnitude of these differences is small, more experimentation would be required to determine if this response is real or just coincidental.

Comparisons of the percent error for EFI and WSFI in Table 8 indicated that the precision of the SORGF and SORGF/WS models were highly correlated within a given treatment and year. Fig. 18 shows the percent error of the EFI simulations plotted against the percent error of the WSFI for a given quantity of water applied in the same growing season. If all of the points fell directly on the transecting line, then the average percent error would be equal in all four cases. While the points do not fall directly on this line they do indicate a strong linear correlation. Thus, the SORGF/WS model simulating WSFI appears to provide the same level of precision as the original SORGF model simulating EFI, for a given treatment and year.

It should be noted that the location of the neutron access tubes in the field could have led to some degree of imprecision (Fig. 2). Since the tubes were located in the planted rows, soil moisture measurements did not account for moisture levels directly under the furrow. Thus, the observed values could be slight underestimates of the average soil water level under EFI conditions. In the case of WSFI the observed soil water levels could be overestimating or underestimating the actual average level depending on the magnitude of dry and wet regions under the

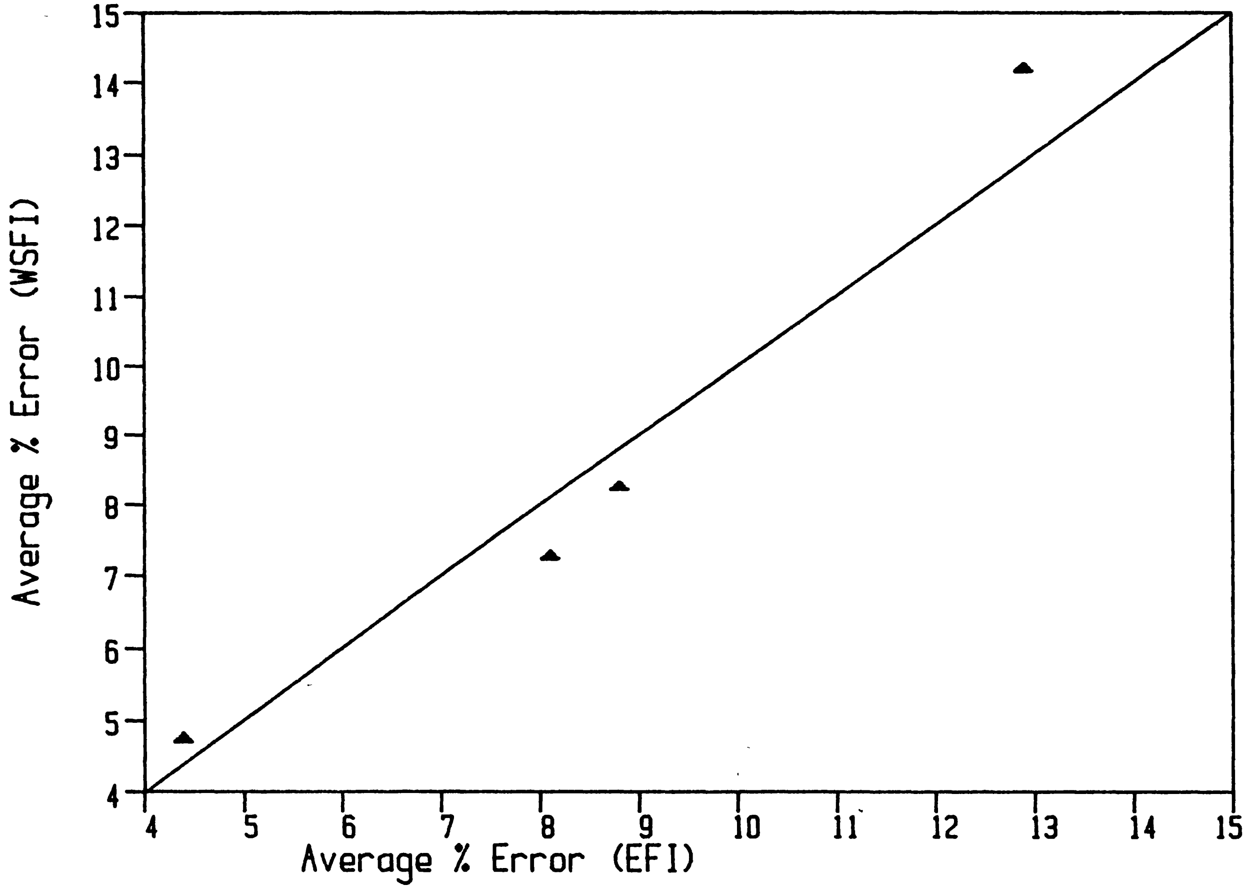

Fig. 18. The correlation between the average % error of WSFI and EFI simulations under the same irrigation frequency and year.

dry and irrigated furrows, respectively.

Since the SORGF/WS model appeared to simulate changes in the soil water balance with reasonable precision. It was then of interest to compare the soil water balance components under EFI and WSFI, in hopes of gaining some insight into the properties of WSFI. The SORGF/WS model was developed on the premise that evaporative losses from the soil surface were reduced under WSFI. The seasonal cumulative evaporation from the soil for all treatments over both growing seasons is presented in Table 11. Each value is presented in terms of quantity and as a percentage of the corresponding cumulative ET. Comparisons of ΣEs under a high irrigation frequency indicated that evaporative losses were reduced by approximately 2 cm. Under a low irrigation frequency, the use of WSFI reduced ΣEs by 1.0 to 1.6 cm. The magnitude of these reductions agreed with rough estimates of soil evaporation made by Tsegaye (1986). He approximated Es by calculating the net water loss from the top 15 cm of the profile for each treatment (Table 12). The magnitude of these estimates appear small since they ignore evaporative losses after a precipitation event. However, ΣEs was reported to be less under WSFI than under EFI.

Table 13 shows simulated seasonal plant evaporation, Ep, or transpiration for all treatments over both growing seasons using the same format as Table 11. Ep increased by 1.0 cm to 1.2 cm when WSFI was used. This indicates that

TABLE 11.

Simulated cumulative evaporation from the soil for all treatments over the 1984 and 1985 growing season.

Method of Irrigation	Irrigation Frequency (days) 7 & 14 Quantity (cm)	7 & 14 %Et	10.5 & 21 Quantity (cm)	10.5 & 21 %Et
1984:				
EFI	20.06	45.2	18.28	42.5
WSFI	18.07	41.6	16.62	39.1
1985:				
EFI	23.22	49.8	20.64	46.3
WSFI	20.64	46.2	19.63	44.1

TABLE 12.

Cumulative evaporation from the soil estimated by soil water losses from the top 15 cm of the profile.[1]

Treatment	Year	
	1984	1985
	---------- cm ----------	
EFI - 14	13	13
WSFI - 7	10	11
EFI - 21	9	10
WSFI - 10.5	7	8

[1] (Tsegaye, 1986).

TABLE 13.

Simulated cumulative plant evaporation for all treatments over the 1984 and 1985 growing season.

Method of Irrigation	Irrigation Frequency (days)			
	7 & 14		10.5 & 21	
	Quantity (cm)	%Et	Quantity (cm)	%Et
1984:				
EFI	24.34	54.8	24.71	57.5
WSFI	25.38	58.4	25.88	60.9
1985:				
EFI	23.39	50.2	23.90	53.7
WSFI	24.59	53.8	24.93	55.9

the model is allowing the plant to absorb the water saved from the reduction of soil evaporation. Table 9 containing the cumulative ET values also confirms this response by showing no significant reduction in total evaporation when WSFI is used. Thus, it can be concluded that the SORGF/WS model does reduce the evaporation from the soil and allows this moisture to be extracted by the plant for growth and development. Another factor in the soil water balance is quantity of water accounted for as excess by equation [3]. However no significant reductions in drainage were observed between the WSFI and EFI simulations (Table 14).

Simulation of Grain Yield

Although the major focus of this study was not the modeling of plant growth factors and dry matter accumulation, it is of interest since the main objective of WSFI is producing stable or increased yields while using less water. Simulated vs observed grain yields for the 1984 and 1985 growing season are presented in Table 15. Actual data indicated that WSFI produced a higher yield than EFI when a given amount of water was applied (Tsegaye, 1986). Neither the SORGF nor the SORGF/WS model responded to the level or mode of irrigation. No appreciable differences between treatments within a given year were observed. This indicates modification may be required to modeled relationships between soil water and plant growth factors. It should be noted that the SORGF model is very sensitive to

TABLE 14.

Simulated cumulative excess water for all treatments in 1984 and 1985.

Method of Irrigation	Irrigation Frequency (days)			
	1984		1985	
	7 & 14	10.5 & 21	7 & 14	10.5 & 21
	cm			
EFI	7.23	3.75	14.21	8.52
WSFI	7.23	3.23	13.63	8.20

TABLE 15.

Simulated vs observed grain sorghum yields for all treatments for 1984 and 1985 growing season at Goodwell, OK.

Method of Irrigation	Irrigation Frequency (days)			
	7 & 14		10.5 & 21	
	Simulated	Observed	Simulated	Observed
<u>1984</u>:	kg/ha			
EFI	6410	7340a	6398	6410 b
WSFI	6409	7360a	6397	7070ab
<u>1985</u>:				
EFI	6241	6510a	6225	5270 b
WSFI	6240	6930a	6214	6250a

$LSD_{0.05}$ for observed yields 1984, 905 kg/ha;
for observed yields 1985, 803 kg/ha.

both the number of leaves and the maximum size of each leaf which must be assigned to the plant prior to simulation (Table 1). Thus, inprecision in the assignment of these parameters will have a large impact on development and yield. Nevertheless, simulated yields for the 1984 growing season were greater than those for 1985, which is consistent with the observed data. Although these simulations were not responsive to the method of irrigation, simulated grain yields were within 18 percent of the observed yields for all treatments. This fact gives some credibility to the techniques used for the calibration and modification of the SORGF model developed for this research.

CHAPTER VI

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

Field studies have indicated that the use of wide spaced furrow irrigation, WSFI, may provide a means of maintaining reasonable grain sorghum yields in the Oklahoma Panhandle while using less irrigation water. While this response was well documented, little was known about the mechanism of this response. A well known grain sorghum growth model, SORGF, was selected as a possible tool for research into this phenomenon. A Turbo Pascal version of the model was obtained which permitted its use on a microcomputer. The soil water balance computations were rigorously reviewed and calibrated for a Richfield clay loam at Goodwell, OK. Since the original SORGF model did not allow for a nonhomogeneous application of water, modifications were made to account for the soil water balance under WSFI. This modified version of the model was designated SORGF/WS. Once both versions of the model were calibrated, the soil water balance of grain sorghum was simulated for the 1984 and 1985 growing seasons at Goodwell, OK. The results produced from these simulations were then compared to actual soil water data collected by others over the same period. Of secondary importance was the simulated yield response, which was also compared to observed data.

Conclusions

The calibrated SORGF model made reasonable estimates of the changes in the soil water balance over the growing season under every furrow irrigation, EFI. Comparisons of simulated and observed soil water balance values indicated that the precision of the SORGF/WS model under WSFI conditions was not significantly different than the precision of the original SORGF model under EFI, within a given year and quantity of applied water. It follows that the SORGF/WS model is a valid method of estimating the soil water balance under WSFI conditions. Simulated results did indicate a reduction in soil surface evaporation under WSFI as compared to EFI. The magnitude of these savings were not large enough to create any differences in yield between methods of irrigation. However, simulated and observed yields never differed by more than 18 percent.

The calibration of the SORGF model and the development of the SORGF/WS model, now provide a means for future study into irrigation management methods. Different types of irrigation scheduling techniques can now be simulated with some confidence in the predicted soil water level. In the future it may be possible to use the SORGF model in conjunction with decision making software to help producers maximize yields and conserve water.

Recommendations

Since the soil water balance portion of the SORGF model appears to be sound, the next logical step is a detailed review of the plant growth factors within the model. Special emphasis should be placed on plant and soil water relationships to determine why yield does not respond to different levels of applied water. Since wind movement is large in the high plains region the addition of an advective component may be desirable since it would make the model more theoretically sound. Future field experiments should be designed to provide all the required inputs for the SORGF model, including leaf number and area. Neutron access tubes should be located directly in the furrow as well as in the crop row, to provide a better accounting of the soil water balance.

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APPENDIXES

APPENDIX A

PASCAL SOURCE CODE FOR MODIFIED SOLWAT PROCEDURE USED IN SORGF/WS

```
PROCEDURE SOLWAT1 (I: INTEGER; VAR ADR: REAL);    { WSFI version }

 Var   J         : Integer;
      ULWS      : Real;            { Upper Limit of SW on a WSFI Event }
      L,L1,L2,L3: Real;            { size of evaporative regions }

Procedure WSEVAP(Var ES    :Real;   { Evap for Soil }
                 Var T     :Real;   { Time parameter in StageII evap }
                 Var SumeS1:Real;   { Sum of Stage I Evap }
                 Var SumeS2:Real);  { Sum of Stage II Evap }


   Begin
    IF (SUMES1 - U) >= 0.0 THEN
     BEGIN
       IF (PRECIP - SUMES2) >= 0.0 THEN
        BEGIN
          PRECIP:= PRECIP - SUMES2;
          SUMES1:= U - PRECIP;
          T:= 0.0;
          IF (PRECIP - U) > 0.0 THEN
           SUMES1:= 0.0;
          SUMES1:= SUMES1 + EOS;
          IF (SUMES1 - U) > 0.0 THEN
           BEGIN
             ES:= EOS - 0.4 * (SUMES1 - U);
             SUMES2:= 0.6 * (SUMES1 - U);
             T:= SQR(SUMES2/CONA)
           END
            ELSE
          ES:= EOS;
        END
         ELSE
        BEGIN
          T:= T + 1.0;
          ES:= CONA * SQRT(T) - SUMES2;
          IF PRECIP <= 0.0 THEN
           BEGIN
             IF ES > EOS THEN
               ES:= EOS
           END
            ELSE
           BEGIN
             ESX:= 0.8 * PRECIP;
             IF ESX <= ES THEN
              ESX:= ES + PRECIP;
             IF ESX > EOS THEN
              ESX:= EOS;
             ES:= ESX
           END;
          SUMES2:= SUMES2 + ES - PRECIP;
          T:= SQR(SUMES2/CONA)
        END
     END
      ELSE
```

```
    BEGIN
      IF (PRECIP - SUMES1) >= 0.0 THEN
        SUMES1:= 0.0
      ELSE
        SUMES1:= SUMES1 - PRECIP;
      SUMES1:= SUMES1 + EOS;
      IF (SUMES1 - U) > 0.0 THEN
      BEGIN
         ES:= EOS-0.4*(SUMES1 - U);
         SUMES2:= 0.6 * (SumeS1 - U);
         T:= SQR(SUMES2/CONA)
      END
        ELSE
      ES:= EOS
    END;
   IF ES < 0.0 THEN ES:= 0.0;
  End;  { procedure WSFIevap }

 BEGIN

   ULWS:=23.4;
   L1:=33; L2:=38; L3:=71; L:=142;
   Irr:=0.0;
   SwObs:=0;
   SwRes:=0;
   PRECIP:= RAIN[I];
   If (IrrFlag)='Y' then          { add irrigation }
    Begin
     For j:= Adv to Nirr do
       If (IrrMat[j,1]=I) then
        Begin
         Precip:= Precip + IrrMat[j,2];
         Irr:=IrrMat[j,2];
         IrrSum:=IrrSum+Irr;
         Adv:=Adv+1;
         Writeln(DevFvar,'-----> Irrigation on ',I:4,' of ',Irr:5:2,' cm');
         LineSum:=LineSum+1;
         If (LineSum Mod PageSize)=0 then PrintVarName;
        End;
    End;

If I=Isow then
 Begin
  DcycleFlg:=0;
  SumeS1D:=0;
  SumeS2D:=0;
  Td:=0;
  SumeS1w:=0;
  SumeS2w:=0;
 End;

If (Irr>0) then               { Initialize var on irr event }
 Begin
  DcycleFlg:=1;
  SumeS1W:=0;
```

```
  SumeS2W:=0;
  Tw:=0;
  SumeS2M[1]:=0;
  Tm[1]:=0;
  SumeS1M[1]:=0.6 ;            { Set Sum Stage I Evap for mid zone }
 End;

 If DcycleFlg=1 then
  Begin                                  { Begin WSFI drying cycle }
    EsmSum:=0; S2Msum:=0;
    Precip:=Precip-Irr;
    WSevap(Esd,Td,SumeS1D,SumeS2D);
    WSevap(Esm[1],Tm[1],SumeS1M[1],SumeS2M[1]);
    Precip:=Precip+Irr;
    WSevap(Esw,Tw,SumeS1W,SumeS2W);
    Es:= Esd*(L3/L) + Esw*(L1/L) + Esm[1]*(L2/L);
     For j:= Adv to Nirr do              { Exit drying cycle and avg }
       If (IrrMat[j,1]=I+1)  then
        Begin
         DcycleFlg:=0;
         SumeS2D:=((SumeS2D*L3) + (SumeS2W*L1)+ (SumeS2M[1]*L2))/L);
         Td:=Sqr(SumeS2D/Cona);
        End;
       If Esd/Esw=0.9 then               { Exit Criteria }
       If SumeS2w)1.2 then
        Begin
         DcycleFlg:=0;
         SumeS2D:=((SumeS2D*L3) + (SumeS2W*L1)+ (SumeS2M[1]*L2))/L);
         Td:=Sqr(SumeS2D/Cona);
       End;
  End
    Else
  Begin                                  { Non WSFI cycle }
    WSevap(Esd,Td,SumeS1D,SumeS2D);
    Es:=Esd;
  End;                                   { End Es Calculations }

   IF DLAI[I] ) 3.0 THEN
     EP:= EO - ES
   ELSE
   BEGIN
     EP:= 0.53 * SQRT(DLAI[I]) * EO
   END;
   IF EP ( 0.0 THEN EP:= 0.0;
   ET:= ES + EP;
   IF (EO - ET) ( 0.0 THEN
   BEGIN
     ET:= EO;
     EP:= ET - ES
   END;
   RF:= 0.0;
   FNUM:= EXP(5.84*(UL-SW)/UL)*2.896468E-5;
   FOR K:= 1 TO 6 DO
   BEGIN
     RF:= RF+WK[K]*COS(6.28319*K*FNUM*DELT)
```

```
  END;
  WATSCO:= WK[7] + 2.0 * RF;
  EP:= EP * WATSCO;
  ET:= ES + EP;
  XET[I]:= ET;
  SW:= SW - ET + RAIN[I]+ Irr;
  IF SW < 0.0 THEN SW:= 0.0;
  IF SW > UL THEN                     { calc excess irr water }
    Begin
      ExcessWater:=(Sw-UL)+ExcessWater;
      SW:= UL;
    End;
  IF Irr>0 then                       { Adjust WSFI upper limit }
    If SwPrev<=23.4 then
      If Sw>23.4 then
       Begin
        ExcessWater:=(Sw-23.4)+ExcessWater;
        Sw:=23.4;
       End;
  If (SwFlag)='Y' then
   Begin
    For j:= Adv2 to Nsw do            { adjust Soil Water Counter }
      If (SwMat[j,1]=I) then
       Begin
        SwObs:=SwMat[j,2];
        SwRes:=SW-SwObs;              { Soil water residual analysis }
        SumResSq:=SumResSq+Sqr(SwRes);
        SumRes:=SumRes+ABS(SwRes);
        SumObsSq:=SumObsSq+Sqr(SwObs);
        SumObs:=SumObs+(SwObs);
        SumPreSq:=SumPreSq+Sqr(Sw);
        SumPre:=SumPre+(Sw);
        ResNum:=ResNum+1;
        If SwRes>0 then
          Begin
            SwOverEst:=SwOverEst+1;
            RunStr:=RunStr + '+';
          End
           Else
          Begin
            SwUndrEst:=SwUndrEst+1;
            RunStr:=RunStr + '-';
          End;
        Adv2:=Adv2+1;
       End;
   End;
  EPsum:=EPsum+EP;
  ESsum:=ESsum+ES;
  RainSum:=RainSum+Rain[i];
  SwPrev:=SW;
END;
```

APPENDIX B

MODIFICATION OF THE ALBEDO EQUATION

Determination of evaporative rates from the plant and soil surface are dependent on the potential evaporation above and below the canopy. The potential evaporation from the soil surface, Eso, and above the plant canopy, Eo, are calculated with procedure EVAP within the SORGF model. Potential evaporation is a function of net radiation, H, added to the field system on a given calendar day. The value of H is determined by equation [13] located at line number 190 in the EVAP subroutine within the original SORGF source code (Maas and Arkin, 1978)..

```
H = (1-ALBEDO)*SOLRAD[I] + R6                        [13]
```

where;

```
ALBEDO     = reflectance
SOLRAD[I]  = solar radiation for calendar day I, Ly/day
R6         = net thermal radiation, Ly/day
```

Albedo is determined using equation 14 located at line 130 within the same subroutine.

```
ALBEDO = 0.3367 - 0.1867*EXP(-0.6*DLAI[I])           [14]
```

where;

```
DLAI[I] = leaf area index for calendar day I
```

Albedo represents the degree of solar reflection from the field surface. It can be observed from equation 13, that as albedo increases, the value of net radiation decreases, eventually causing a reduction in Es and Ep.

Fritschen (1967) reported albedo values between 0.19 and 0.22 for grain sorghum near maturity. Studies of cotton and grain sorghum by Ritchie (1971) and Stone (1986; personal communication) resulted in albedo estimates of 0.23 for sorghum crop canopies near full cover. Ritchie (1972) represented albedo for developing grain sorghum as a linear function of LAI by equation [15]

$$\epsilon = \epsilon_s + 0.25(0.23 - \epsilon_s)LAI \qquad [15]$$

where;

ϵ = Albedo
ϵ_s = Albedo from a bare soil surface

and the albedo at full cover is 0.23. Both equations [14] and [15] assume that the albedo value returned when no crop is present, (LAI=0), is that of a bare soil, and maximum albedo is achieved at full canopy development (LAI=4). Examining the performance of equation [13] within the SORGF model revealed that excessively high values for albedo were being generated during the growing season. Albedo values exceed the documented maximum value of 0.23 early in the growing season (LAI=0.94), and continued to increase to 0.32 at full canopy development (LAI=4.0). This fact caused the model to underestimate Es and Ep during later stages of plant growth. To correct this problem equation [14] was modified so that maximum albedo values during late season development would approach the documented maximum.

ALBEDO = 0.23 - 0.08*EXP(-0.6*DLAI[I]) [16]

Figure 19 shows albedo vs LAI for the proposed equation along with those generated by equations [14] and [15].

Albedos for a bare soil have been reported between 0.11 and 0.23 by Gates and Hanks (1967). Fritschen (1967) reported a range of albedos between 0.14 and 0.24 depending on surface moisture conditions. A relatively small bare soil albedo of 0.15 was used in the original SORGF model, due to the dark color of the soil at the Temple, TX location. Since no specific data was available for soil surface albedo at the Goodwell, OK location, soil surface albedo was left unchanged. However, if such data were available, the albedo equations within the model should be modified accordingly.

Changing the albedo equation in the SORGF model resulted in increased evaporation during the growing season. Simulated values of ΣEp for the four treatments used during the 1984 and 1985 growing seasons are presented in Table 16. Evaporation from the soil was also increased by 4 to 5 percent. However, the modification had a greater impact on Ep due to large differences between equations [14] and [16] late in the growing season when Ep is the dominant form of evaporation. All simulations of the Goodwell location were executed using the modified albedo equation.

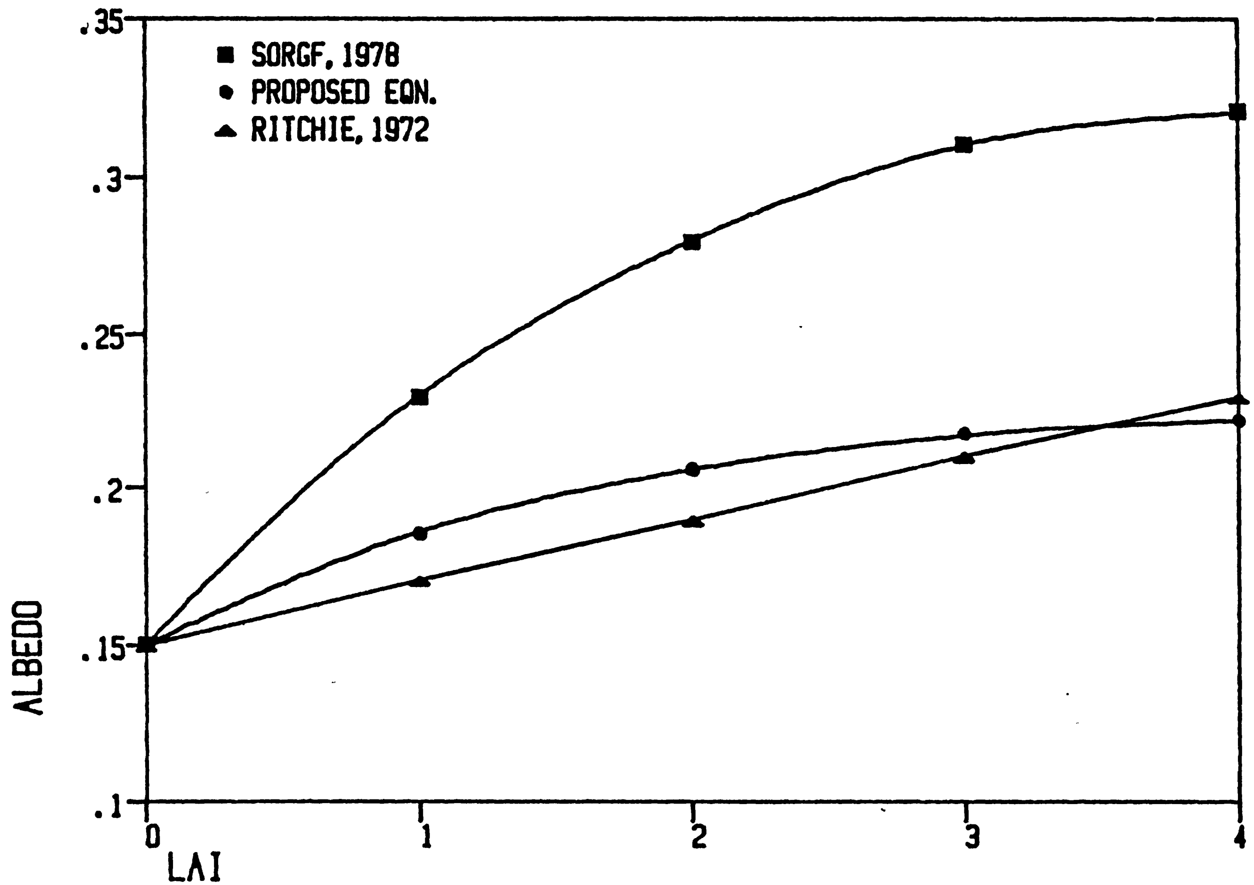

Fig. 19. Performance of three albedo equations.

TABLE 16.

Simulated cumulative plant evaporation over the 1984 and 1985 growing seasons using three different albedo equations.

Equation	Treatment EFI-14	WSFI-7	EFI-21	WSFI-10.5
	----------------	cm	----------------	
<u>1984</u>:				
SORGF, 1978	21.5	22.4	21.9	23.0
Proposed eqn.	24.3	25.4	24.7	25.9
Ritchie, 1972	25.0	26.0	25.3	26.6
<u>1985</u>:				
SORGF, 1978	20.9	22.0	21.4	22.3
Proposed eqn.	23.4	24.6	23.9	25.0
Ritchie, 1972	24.0	25.3	24.0	25.6

APPENDIX C

MODEL INPUT PARAMETERS

Parameter	Input Value	Definition
N	19	Maximum number of leaves
ROSPZ	66	Row spacing, cm
P	87728 (1984)	Population, Plants/ha
	77398 (1985)	,,
ALT	36.5	Latitude, degrees N
SW	25.9	Beginning soil water level, cm
UL	25.9 (EFI)	Max. Soil Water level, cm
,,	23.4 (WSFI)	,,
SDEPTH	5	Planting Depth, cm
MO,ND,IYR	6,4,84	Date of planting in 1984
,,	5,17,85	Date of Planting in 1985
XMAX(1)	0.46	Leaf area by leaf, cm
XMAX(2)	3.70	
XMAX(3)	5.39	
XMAX(4)	8.26	
XMAX(5)	10.90	
XMAX(6)	13.51	
XMAX(7)	22.91	
XMAX(8)	36.27	
XMAX(9)	67.81	
XMAX(10)	119.16	
XMAX(11)	172.15	
XMAX(12)	247.49	
XMAX(13)	308.79	
XMAX(14)	328.30	
XMAX(15)	347.83	
XMAX(16)	339.87	
XMAX(17)	269.13	
XMAX(18)	162.64	
XMAX(19)	55.89	

APPENDIX D

1984 AND 1985 WEATHER DATA

1984 WEATHER DATA:

CALENDAR DAY	TEMPERATURE °C MAXIMUM	MINIMUM	SOLAR RADIATION Ly/day	RAINFALL cm
155	26.37	13.34	466.2	0.00
156	33.54	13.80	709.0	0 00
157	34.71	17.02	633.1	0.00
158	31.20	13.26	695.5	0.00
159	35.06	18.43	717.0	0.00
160	33.34	10.90	741.0	0.00
161	29.25	15.39	723.0	0.00
162	28.21	14.17	294.7	0.00
163	29.91	16.33	415.2	0.60
164	34.99	17.28	723.0	0.00
165	34.22	18.79	598.5	0.00
166	30.46	16.11	573.9	0.00
167	32.94	16.63	623.3	0.00
168	32.54	17.63	611.0	0.70
169	34.08	18.88	597.2	0.00
170	23.76	17.54	262.0	0.00
171	28.73	15.18	438.6	0.00
172	32.15	17.99	541.4	0.00
173	36.21	18.79	520.6	0.00
174	37.48	18.79	683.9	0.00
175	30.39	19.37	489.4	0.00
176	31.33	16.16	481.3	0.00
177	37.63	18.88	671.6	0.30
178	35.34	17.06	684.5	0.10
179	31.01	18.25	661.4	0.00
180	38.10	15.52	662.6	0.10
181	34.02	16.63	721.0	0.00
182	33.88	16.63	707.0	0.00
183	32.48	18.74	496.4	0.00
184	34.85	16.42	661.3	0.00
185	37.10	18.25	633.7	0.70
186	28.84	17.28	592.9	0.00
187	36.06	16.76	564.4	0.00
188	38.56	15.43	738.0	0.10
189	38.17	21.27	716.0	0.00
190	38.41	18.25	728.0	0.00
191	37.94	19.78	705.0	0.00
192	36.50	19.47	546.3	0.50
193	31.39	18.30	588.2	0.30
194	33.67	15.31	697.8	0.00
195	36.36	18.12	635.7	0.00
196	38.49	21.04	694.3	0.00
197	34.29	19.10	439.0	0.60
198	29.55	17.41	649.9	0.10
199	32.02	16.46	629.3	0.00
200	34.29	16.03	695.0	0.00
201	37.10	18.65	658.9	0.00

202	37.18	16.80	695.1	0.00
203	37.25	19.01	667.4	0.00
204	36.80	20.29	627.9	0.00
205	37.03	18.43	637.3	0.00
206	33.00	16.42	622.9	0.00
207	30.21	15.47	447.3	0.00
208	34.92	16.46	600.4	0.10
209	32.02	17.72	519.2	0.00
210	29.43	18.30	457.4	0.00
211	33.54	17.37	604.8	0.00
212	34.85	19.10	628.8	0.00
213	35.49	18.16	544.4	0.00
214	33.47	17.85	582.1	0.00
215	33.34	17.06	553.2	0.00
216	35.63	17.28	654.9	0.00
217	36.73	20.43	541.2	0.40
218	34.64	18.79	520.9	0.20
219	36.65	20.38	539.5	0.00
220	34.15	19.15	389.7	0.10
221	29.14	18.92	271.9	0.10
222	30.52	18.56	454.3	0.00
223	20.94	17.85	170.6	0.70
224	28.73	17.59	473.3	0.00
225	30.95	15.69	573.3	0.00
226	31.58	16.29	605.7	0.00
227	33.20	17.81	557.7	0.00
228	33.61	19.47	524.5	0.60
229	33.27	18.12	569.8	0.00
230	34.92	18.34	641.9	0.00
231	33.95	19.01	614.5	0.00
232	33.14	18.07	595.1	0.00
233	37.94	20.66	594.6	0.00
234	31.39	20.15	599.1	0.00
235	31.01	20.25	377.6	0.00
236	29.31	18.43	315.6	0.10
237	33.54	19.01	535.9	0.00
238	34.08	19.74	541.2	0.00
239	35.34	19.97	600.9	0.00
240	36.95	18.25	586.3	0.00
241	39.04	17.41	601.7	0.00
242	39.85	18.52	593.2	0.00
243	38.72	15.99	565.2	0.00
244	35.70	20.06	598.7	0.00
245	35.56	18.74	559.9	0.00
246	25.52	15.77	495.2	2.90
247	27.75	12.03	601.4	0.00
248	30.27	12.72	591.6	0.00
249	33.34	14.55	584.5	0.00
250	34.15	17.68	587.4	0.00
251	35.85	17.54	587.7	0.00
252	29.73	12.56	570.8	0.00
253	33.74	13.22	563.8	0.00
254	38.17	15.22	547.1	0.00

1985 WEATHER DATA:

CALENDAR DAY	TEMPERATURE °C MAXIMUM	MINIMUM	SOLAR RADIATION Ly/day	RAINFALL cm
137	23.33	11.11	502.9	0.00
138	17.78	8.89	251.8	0.00
139	23.89	7.78	487.9	0.00
140	26.67	9.44	502.1	0.00
141	24.44	12.78	511.9	0.00
142	20.56	7.22	281.4	0.00
143	19.44	8.89	366.2	0.00
144	25.56	10.00	637.2	7.49
145	28.89	11.67	627.4	0.00
146	31.11	12.78	625.9	0.00
147	33.89	12.22	598.6	0.00
148	30.00	15.56	615.0	0.00
149	31.67	12.22	620.3	0.00
150	36.67	13.33	599.4	0.00
151	34.44	10.56	653.5	0.00
152	29.44	13.33	525.6	0.00
153	32.78	15.56	639.1	0.00
154	25.56	13.89	619.9	0.00
155	22.78	13.89	265.1	0.00
156	16.67	12.22	166.5	0.33
157	17.22	12.78	211.7	3.38
158	28.89	16.11	625.8	0.08
159	36.11	19.44	596.3	0.00
160	37.78	16.67	597.4	0.00
161	27.78	13.89	525.0	0.00
162	35.56	11.67	536.5	0.00
163	25.00	11.11	672.7	1.00
164	22.78	12.22	507.9	0.00
165	30.56	14.44	609.0	0.00
166	36.11	16.11	608.1	0.00
167	33.33	13.33	566.9	0.20
168	36.67	18.89	520.0	0.00
169	28.89	14.44	599.5	0.03
170	26.11	11.67	594.9	0.00
171	30.56	15.56	499.8	0.00
172	35.00	18.89	650.4	0.00
173	36.67	13.33	568.0	0.00
174	32.22	17.22	646.6	0.00
175	37.22	17.22	619.5	0.00
176	35.00	18.89	629.2	0.00
177	32.22	16.67	389.3	0.00
178	25.56	8.89	529.3	0.00
179	27.78	10.00	651.4	0.00
180	33.89	15.00	629.5	0.00
181	32.22	17.78	600.0	0.00
182	28.89	11.67	530.6	0.00
183	28.89	15.56	558.2	0.00

184	30.00	13.89	580.9	0.33
185	31.11	13.89	640.7	0.00
186	30.00	14.44	594.5	0.00
187	29.44	15.00	627.5	0.00
188	31.11	15.00	612.9	0.00
189	31.11	15.00	632.3	0.00
190	28.89	13.89	613.6	0.00
191	36.95	19.15	584.6	0.00
192	38.49	20.71	640.7	0.00
193	38.49	20.99	576.7	0.00
194	40.34	21.04	630.4	0.00
195	38.17	19.56	609.3	0.40
196	30.52	18.12	538.4	0.10
197	34.64	15.35	559.2	0.00
198	38.49	20.71	622.7	0.00
199	39.93	19.97	606.2	0.00
200	36.36	20.20	476.7	0.10
201	34.71	17.37	440.7	0.00
202	36.21	18.74	506.5	0.00
203	33.81	19.24	441.0	0.00
204	34.64	17.81	451.7	0.00
205	29.73	17.33	231.8	0.20
206	31.64	17.46	581.8	0.00
207	32.02	14.97	528.3	0.00
208	33.74	16.50	489.2	0.00
209	38.49	20.01	580.4	0.80
210	33.34	18.38	475.9	0.00
211	37.48	18.88	525.0	0.00
212	33.47	20.90	531.9	0.00
213	30.03	17.94	303.2	1.70
214	33.61	18.21	528.5	0.30
215	36.50	20.57	514.0	0.00
216	32.74	17.81	509.8	0.00
217	35.49	17.63	616.8	0.00
218	40.09	18.52	563.4	0.00
219	37.03	18.38	583.2	0.00
220	37.94	18.30	602.2	0.00
221	38.64	17.99	534.8	0.00
222	30.21	14.76	575.0	0.00
223	35.27	20.85	471.0	0.00
224	34.43	21.51	545.5	0.00
225	34.99	17.85	549.9	0.00
226	24.27	15.18	216.4	0.00
227	29.31	16.85	426.1	0.00
228	35.99	15.35	546.9	0.00
229	32.15	18.88	584.6	0.00
230	35.13	17.28	490.1	0.20
231	28.09	16.72	278.0	0.00
232	36.06	16.67	531.7	0.00
233	37.33	19.24	481.2	0.00
234	36.43	17.68	572.1	0.00
235	31.14	18.25	284.3	0.00
236	29.73	15.56	527.7	0.00
237	34.02	14.00	472.3	0.00

238	34.02	15.60	541.3	0.00
239	36.06	14.88	557.0	0.00
240	36.80	20.06	529.6	0.00
241	38.80	20.38	534.0	0.00
242	39.77	21.09	551.5	0.00
243	37.94	18.47	568.8	0.00
244	36.95	19.83	513.0	0.00
245	36.36	19.69	501.1	0.00
246	37.86	20.01	530.2	0.20
247	34.15	18.61	510.1	0.10
248	36.50	16.93	522.6	0.00
249	36.73	16.72	528.4	0.00
250	36.36	14.76	546.2	0.00
251	34.64	16.11	501.1	0.00
252	34.50	17.24	367.8	0.00
253	35.27	16.50	404.2	0.00
254	22.67	16.11	118.3	5.90
255	26.54	16.11	298.0	1.30

APPENDIX E

1984 AND 1985 IRRIGATION DATA

1984 IRRIGATION DATA:

CALENDAR DAY	TREATMENT WSFI-7	WSFI-10.5	EFI-14	EFI-21
	cm			
178	3.68	3.69	7.37	7.37
185	3.68	-	-	-
188	-	3.68	-	-
192	3.68	-	7.36	-
199	3.68	3.68	-	7.37
206	3.68	-	7.37	-
208	-	3.68	-	-
213	3.68	-	-	-
220	3.68	3.69	7.37	7.37
227	3.73	-	-	-
229	-	3.68	-	-
234	3.69	-	7.37	-
241	3.68	3.68	-	7.37

1985 IRRIGATION DATA:

CALENDAR DAY	TREATMENT WSFI-7	WSFI-10.5	EFI-14	EFI-21
	cm			
176	3.69	3.69	7.38	7.38
183	3.69	-	-	-
186	-	3.69	-	-
190	3.69	-	7.38	-
198	3.68	3.68	-	7.37
204	3.69	-	7.38	-
207	-	3.67	-	-
211	3.67	-	-	-
218	3.68	3.68	7.36	7.36
225	3.68	-	-	-
228	-	2.32	-	-
232	3.69	-	7.38	-

VITA

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Master of Science

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